Senior Thesis

Groundwater Flow and Contaminant Flow Laboratory Exercises

by
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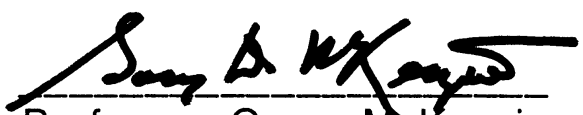
1993

Submitted as partial fulfillment of the requirements for the degree of Bachelor of Science in Geological Sciences at The Ohio State University, Spring Quarter, 1993

Approved by:



Professor Garry McKenzie

ACKNOWLEDGMENTS

I wish to thank Professor Garry McKenzie for suggesting the idea of creating a pair of laboratory exercises as a senior thesis project and also for his guidance in this project and his encouraging comments.

I wish to thank Professor E. Scott Bair and Professor Franklin W. Schwartz for making their hydrogeology courses both educational and enjoyable. My understanding of hydrogeology is based on what I learned in their courses.

I would like to thank Mr. Scott P. O'Neill and Mr. Steve Leslie for their help in trouble-shooting my computer disk and in printing this paper.

Finally, I wish to thank Miss Cathleen Hall. Her suggestion helped me solve a very difficult problem while writing this thesis.

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ABSTRACT

This paper presents two, 2- to 3-hour laboratory exercises for an intermediate level environmental geology course. The first exercise introduces groundwater; it explains the mechanisms which cause groundwater to flow and incorporates factors that influence in which direction and how fast groundwater will flow; including: recharge and discharge boundaries, the effects of highly permeable and confining units, and the effects of topography and pumping wells. The second exercise introduces contaminant movement in groundwater; it provides a discussion of the processes which affect contaminant migration, and it gives simple ways to determine the parameters which affect a contaminant's movement and how these parameters affect the shape of a contaminant plume. It finishes with a detailed discussion of non-aqueous phase liquid (NAPL) behavior and migration. These exercises have not been tested and evaluated; several other exercises should be developed to address related hydrogeology topics appropriate for an environmental geology course.

INTRODUCTION

This paper presents two, 2- to 3-hour laboratory exercises for an intermediate level environmental geology course. Because these exercises are at an intermediate level, they assume the students who will do them have had introductory geology courses and are familiar with geologic maps, cross sections and basic rock types. The first exercise introduces groundwater; it explains the mechanisms which cause groundwater to flow and incorporates factors that influence in which direction and how fast groundwater will flow, including: recharge and discharge boundaries, the effects of highly permeable and confining units, and the effects of topography and pumping wells. The second exercise introduces contaminant movement in groundwater. It provides a discussion of the processes which affect contaminant migration (advection, dispersion, retardation, diffusion...), gives simple ways to determine the parameters (R_f, a_L, a_T, D_L, D_T) which affect a contaminant's movement and how these parameters affect the shape of a plume, and finishes with a detailed discussion of non-aqueous phase liquid (NAPL) behavior and migration.

The purpose of these laboratory exercises is to teach students the fundamental, basic concepts of groundwater flow and contaminant movement in the subsurface, to use these ideas to solve hydrogeologic problems, and to help develop analytic thinking skills

which will help students ask intelligent, informed questions in future environmental pursuits.

While researching this project I discovered that most articles in scientific journals are presented on a graduate level, so they are either beyond my level of education and understanding or beyond what I needed for the exercises. Because of this, it was difficult to find material that I could understand and also scale down for use in an assignment for students with less hydrogeologic training than I have. Consequently, text books, with their numerous illustrations and explanations became my best source of material; an exception to this rule is the article by Jiao (1993) from Ground Water. Jiao's article explained a method for determining the dispersivity and dispersion coefficients by making use of an ideal plume's elliptical shape. I had never learned this technique, but it looked worthy of investigation. I read the article, taught myself the techniques presented in it, and determined this method would fit nicely in the contaminant flow exercise as a way to calculate a_L, a_T, D_L and D_T. Two of the figures which are used in the exercises as problems were also used in two of the hydrogeology courses I took with Professor E. Scott Bair and Professor Franklin W. Schwartz. Figure 1.13 in the groundwater flow exercise was used by Professor Schwartz in his Contaminant Hydrogeology course. Figure 1.14 in the groundwater flow exercise was used by Professor Bair in his Hydrogeology course. It is purely coincidence that these diagrams are included in this paper. While researching this paper I happened to find the same texts used by Professors Bair and Schwartz, and I found these

diagrams in them. I decided, as did my professors, that these illustrations would make good problems, so I used them in the groundwater flow exercise.

When writing the exercises I tried to define the necessary hydrologic terms in a way that is understandable for non-hydrogeology majors. I hope I have accomplished this, and I hope the labs are easy to read and comprehend. I would like to mention that as I began to piece together the two labs they both started out very mathematical. For the first lab I had many questions dealing with Darcy's Law and groundwater velocity. For the second lab I had many problems concerning calculating retardation and the coefficients of dispersion and dispersivity. When I realized this I decided to even the balance, so to speak, and incorporate many conceptual problems into the exercises. Afterall, the purpose of the labs is to teach hydrogeologic concepts and not mathematics. After I began searching for appropriate conceptual problems I decided to include a good discussion of NAPLs. The conceptual NAPL problems are ideal to even the balance with math-oriented problems, because they use important contaminant concepts such as solubility, volatility and residual saturation, and because a significant portion of contaminant spills involve NAPLs. I believe that I have achieved a reasonable balance between using mathematics and applying concepts to solve problems.

Although unintentional, I believe both labs could take longer than the targeted 2 to 3 hours to complete. This is due partly to my

inexperience in creating laboratory exercises and partly because there is much to be learned in the areas of groundwater and contaminant flow. I have tried to incorporate into each exercise a discussion of the major concepts of groundwater flow and contaminant migration and some questions or problems concerning each aspect. Thus, each lab is longer than I anticipated. The first lab contains a problem which asks the students to contour a map of the Great Basin in the southwestern U. S. in order to create a potentiometric surface. As a self test I contoured the map myself to see if it was too difficult. When I finished I decided the contouring was not too difficult, but that it takes too long. Perhaps as a way to shorten the first lab the contoured map, or a partly contoured map, could be given to the students, instead of having them contour it all themselves. I think this would be reasonable for students who are quite familiar with the contour concept and contouring, and the time saved could be used to learn more important aspects of geology. Other savings in time could be achieved by omitting some questions in each exercise. The problems in the contaminant flow exercise that ask students to draw a plume given it's coefficients of dispersion could be omitted. Also, the problems in the groundwater flow exercise which ask students to illustrate groundwater flow directions on the given cross sections by drawing flow paths could be eliminated to save time.

An unexpected problem encountered when producing the first draft of the labs was the size of many of the figures. While typing the first draft I often failed to leave enough room for the figures,

consequently many had to be significantly reduced when I photocopied them into the exercises. The reduction in size of some of the illustrations would make it more difficult for students to complete some of the problems, especially the conceptual problems which ask the students to respond directly on the figures. I have edited the labs since the first draft and have given the figures more space to allow for larger, clearer illustrations of the students' answers.

There are several problems in the contaminant flow lab concerning groundwater velocity, retardation, adsorption, and dispersion and dispersivity which were all derived from studies done at the experimental site in Borden, Ontario. Dr. G. McKenzie had mentioned the possibility of an environmental laboratory manual for use in Canada containing examples from there. These examples may be of use for that purpose.

LAB 1

Groundwater Flow Exercise

Objective The purpose of this lab is to introduce the basic concepts of groundwater flow and to use these concepts to solve hydrogeologic problems.

Introduction Why should one study the occurence and movement of groundwater? There is a great demand for fresh water, yet less than 1% of the world's water is fresh water and 98% of this fresh water occurs as groundwater. Subsurface water is widely used in households to drink, cook and bathe with; it is used extensively by farmers to irrigate crop fields, and it is used by industries as an inexpensive source of water. So, if one understands the behavior of groundwater then one may use this natural resource more safely and efficiently for drinking, irrigation and industrial purposes.

An appropriate topic to begin the study of groundwater is the **hydrologic cycle**. The hydrologic cycle is a cycle of several processes that move water through the atmosphere, over the earth's surface and underground. Let us begin the cycle with **precipitation**. Precipitation occurs when water vapor in the atmosphere condenses to form droplets that fall as rain, or the droplets freeze, as hail or snow. Once the precipitation reaches the earth's surface several processes may occur. **Overland flow** is the process when rain flows over the land surface and into a stream, river or lake. **Runoff** is the process when water flows down a stream or river channel and into a lake or sea. Not all of the precipitation that falls will reach a river, lake or the sea via the land surface; some will seep into the subsurface through pores in the soil and bedrock; this is the process known as **infiltration**. Once underground, water may move horizontally or vertically; this is termed **groundwater flow**. Groundwater may reappear on the earth's surface as springs or by subsurface discharging into rivers, lakes or the ocean. The water can then re-enter the atmosphere by two processes. **Evaporation** is the process where water is vaporized, and **transpiration** is the process by which plants utilize water and then transpire it as vapor into the atmosphere.

Groundwater Flow

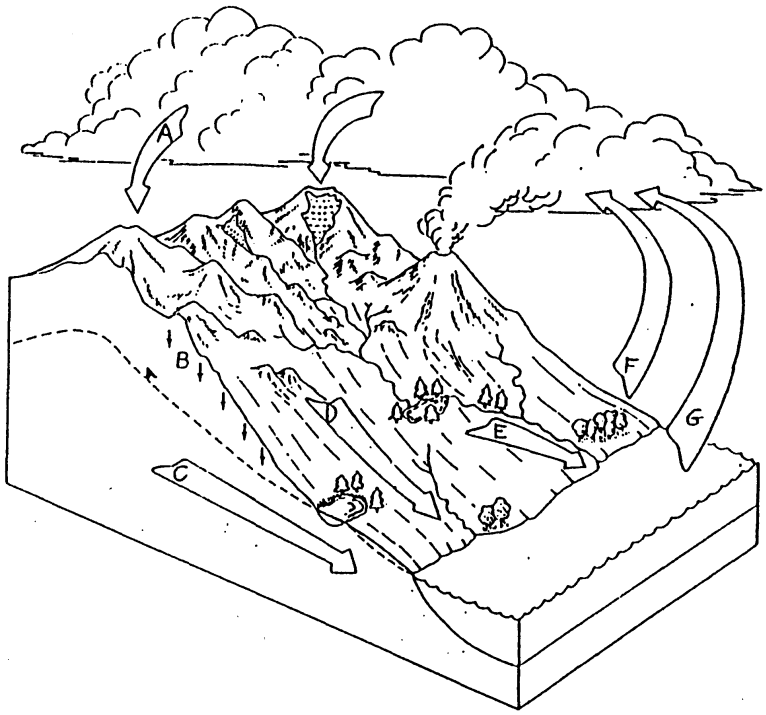

FIGURE 1.1
The hydrologic cycle. Source: Fetter, C. W., 1980, p. 6.

1) Using the information given in the introduction, examine Figure 1.1 and identify the various processes which make up the hydrologic cycle.

A.
B.
C.
D.
E.
F.
G.

As described above water enters the subsurface through pores via the process of infiltration. There are three different zones which water may move through underground. The first zone encountered is the **unsaturated zone**, also known as the zone of aeration or the vadose zone. It lies between the land surface and the water table; the pore spaces in the unsaturated zone contain mostly air and a little moisture. The second zone that water may encounter underground is the **capillary fringe**. This is a thin zone at the base of the unsaturated zone where the pore spaces contain mostly water

and a little air. The water in the pores is held in place by molecular attraction between the water and soil or sediment particles. The third zone underground that water may move through is the **saturated zone**. The pore spaces in the saturated zone are completely filled with water. The saturated zone and the capillary fringe are separated by the **water table**; this is the surface underground where water in pore spaces is at atmospheric pressure. Above the water table any water in pores is at less than atmospheric pressure and below the water table the water in pores is at greater than atmospheric pressure.

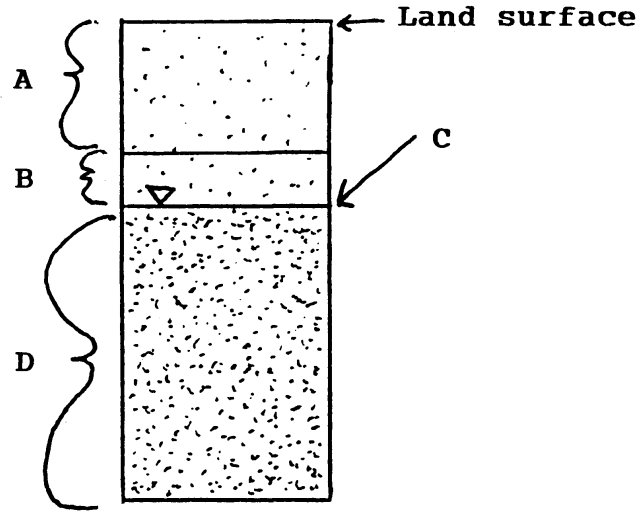

FIGURE 1.2
The different zones in the subsurface.

2) Examine Figure 1.2 and identify the subsurface zones depicted.

A.
B.
C.
D.

When water moves underground it moves through an **aquifer**. An aquifer is a formation of rock or sediment that is saturated with water and is readily permeable, which allows water to travel through it. There are two basic types of aquifers, unconfined and confined (See Figure 1.3 on the next page). **Unconfined aquifers**, also known as water table aquifers, are

nearest to the land surface and are bounded above by the water table. **Confined aquifers** are generally located beneath unconfined aquifers and are separated, or confined, by a confining layer both above and below. A **confining layer** is a layer of sediment or rock that has very low permeability and does not allow water to travel through it.

The level to which water will rise, due to pressure, in wells that are drilled into an aquifer is called the **potentiometric surface**, or the water pressure surface. The potentiometric for an unconfined aquifer is the **water table**. The water pressure surface for a confined aquifer has no special name and is simply referred to as a potentiometric surface (See Figure 1.3 below).

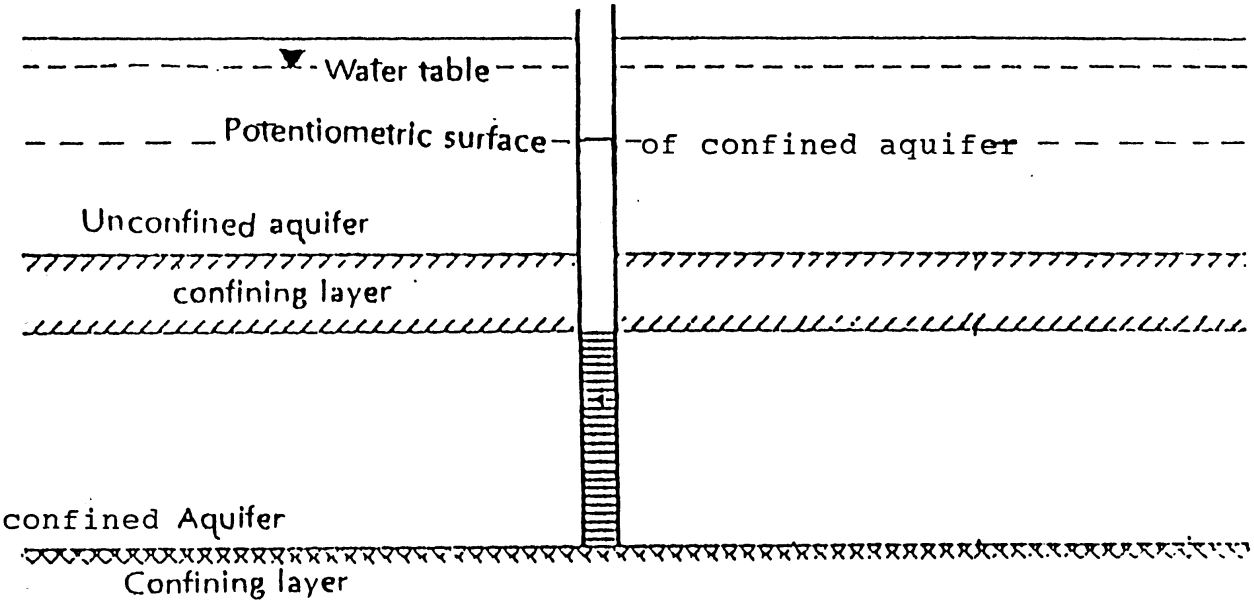

FIGURE 1.3
Water table and potentiometric surface for an unconfined and confined aquifer, respectively. Source: Fetter, C. W., 1980, p. 179.

Wells that are drilled into confined aquifers are called **artesian wells**. If the potentiometric surface for a confined aquifer is above the land surface then a well that is drilled into the confined aquifer will flow water onto the surface; this is called a **flowing artesian well**. In places where the water table intersects the land surface water will **discharge** from the aquifer onto the surface; this will produce a natural spring. The water may

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also discharge into a lake or stream from the aquifer if the water table intersects the stream channel or lake bottom. In areas where the water table is below the land surface, precipitation will infiltrate into the ground and **recharge** the aquifer. Streams and lakes can also recharge an aquifer. If the water table is below a stream channel or lake bottom then water will flow down toward the water table and into the unconfined aquifer.

3) Examine the aquifer in Figure 1.4 below. What processes may occur at the area outlined by **A** during a rainfall?

4) Identify the following parts of Figure 1.4.

B.

E.

F.

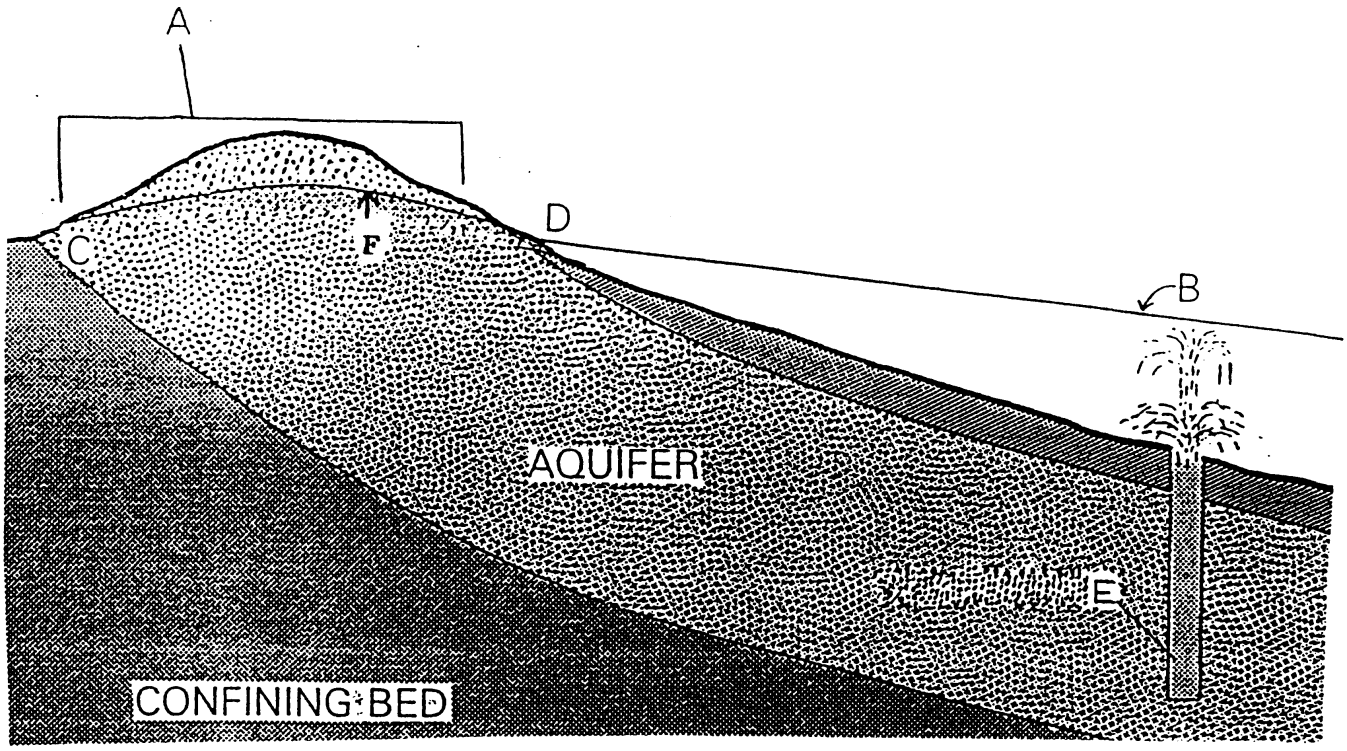

FIGURE 1.4

An aquifer which is both confined and unconfined. Source: Price, Michael, Introducing Groundwater, p. 67.

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5) What distinguishes **B** and **F** from each other in Figure 1.4 ?

6) What might you expect to find on the land surface at points **C** and **D**? Why?

Hydraulic head (h) is a measure of the mechanical energy in water; it consists of two parts; the pressure head (h_p) which is due to the pressure of the surrounding fluid, and the elevation head (z) which is the potential energy stored in the water as a result of lifting the water to some point above a datum (usually above sea level). Thus, $h=h_p+z$. So, the water level measured in a well is called the hydraulic head. How does this differ from a potentiometric surface? The hydraulic heads of many wells drilled into an aquifer can be measured, mapped and contoured to produce a potentiometric surface. So, the hydraulic head measured in a well is a single point used to create a potentiometric surface.

Why should one study hydraulic head? Differences in hydraulic head will tell us which way groundwater will move. There is a very simple way to determine this. Groundwater will move from an area of high hydraulic head to an area of lower hydraulic head, thus groundwater movement can be predicted.

7) Examine the four diagrams in Figure 1.5 on the following page. Assume Assume each rectangle in a diagram is a segment of an aquifer. Draw an arrow in each rectangle to indicate the direction of groundwater flow. Remember that water moves from high to low hydraulic head.

8) What seems counter intuitive about diagram **A**?

Groundwater Flow

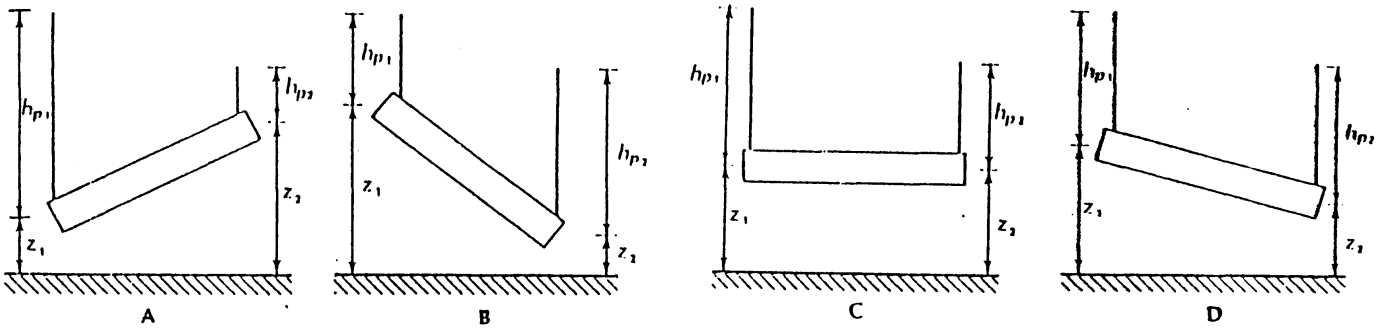


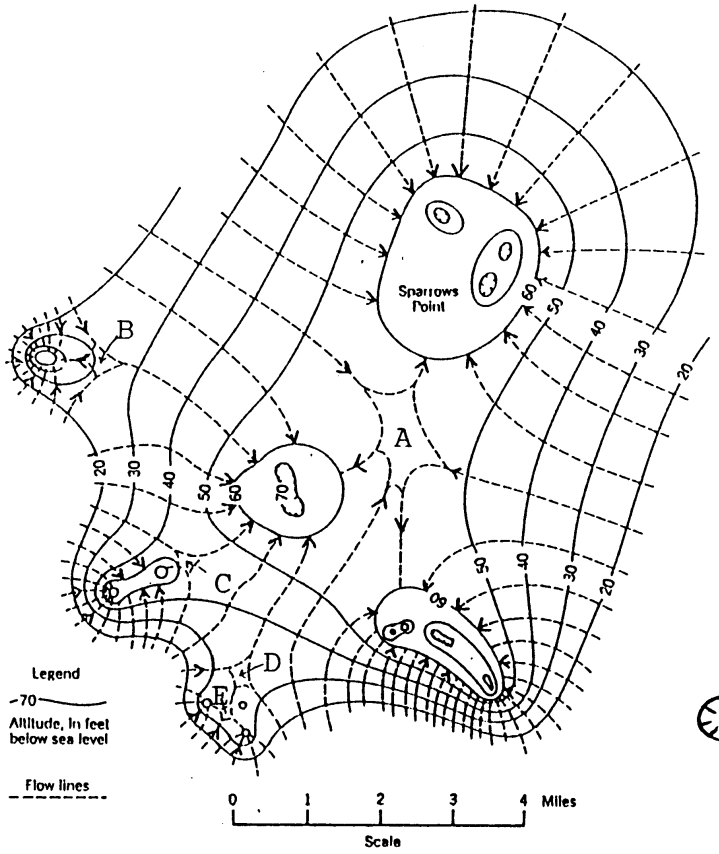
Figure 1.5
Simple hydraulic head diagrams. Source: Fetter, C. W., 1980, p. 122.

9) Can you think of a natural geologic setting where the water would flow as depicted in diagram **A** of Figure 1.5? Sketch your idea below.

Figure 1.6 on the next page shows a **flow net** for the Patuxent Formation. A flow net is a potentiometric surface with flow lines and equipotential lines on it. **Equipotential lines** are contours* that represent lines of equal hydraulic head. **Flow lines** are simply lines that show the direction of groundwater flow. In Figure 1.6 the equipotential lines are solid and the flow lines are dashed; note that the flow lines intersect the equipotential lines at right angles to form a set of curvilinear squares. Points **A** through **E** on Figure 1.6 are **stagnation points**. These are places on a flow net where the water is not moving.

* A contour is a line on a map or chart that connects points of equal value.

Groundwater Flow



Depression in the potentiometric surface created by pumping wells

Figure 1.6
Flow net for the Patuxent Formation. Source: Bennett and Meyer, 1952.

Figure 1.7 on the following page contains some simple rules for contouring, most of which are applicable to flow nets, and which may be useful for problem 10.

10) Figure 1.8 on page 10 shows a map of the Carbonate-Rock Province of The Great Basin in Nevada, Utah, California and Arizona. The hydraulic heads for 52 wells are listed on the map. Create a potentiometric surface by contouring the map using a 250-foot contour interval beginning with the 0-foot contour and ending with the 4500-foot contour.

11) Draw 10 flow lines on the potentiometric surface you created in Figure 1.8 which will show the area's regional groundwater flow directions.

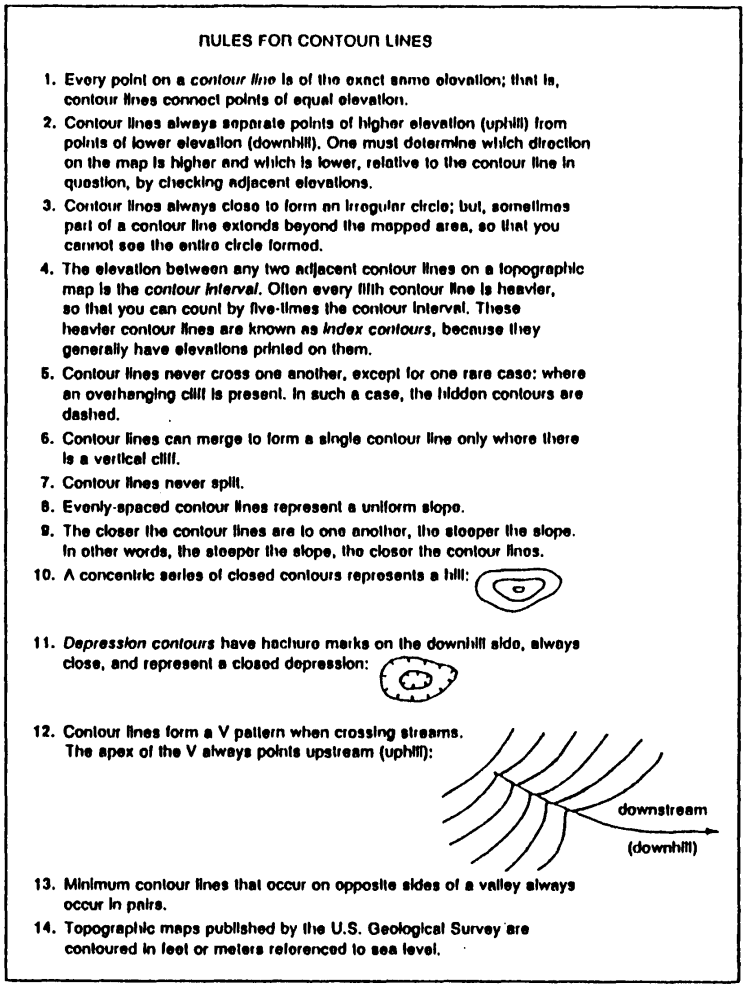


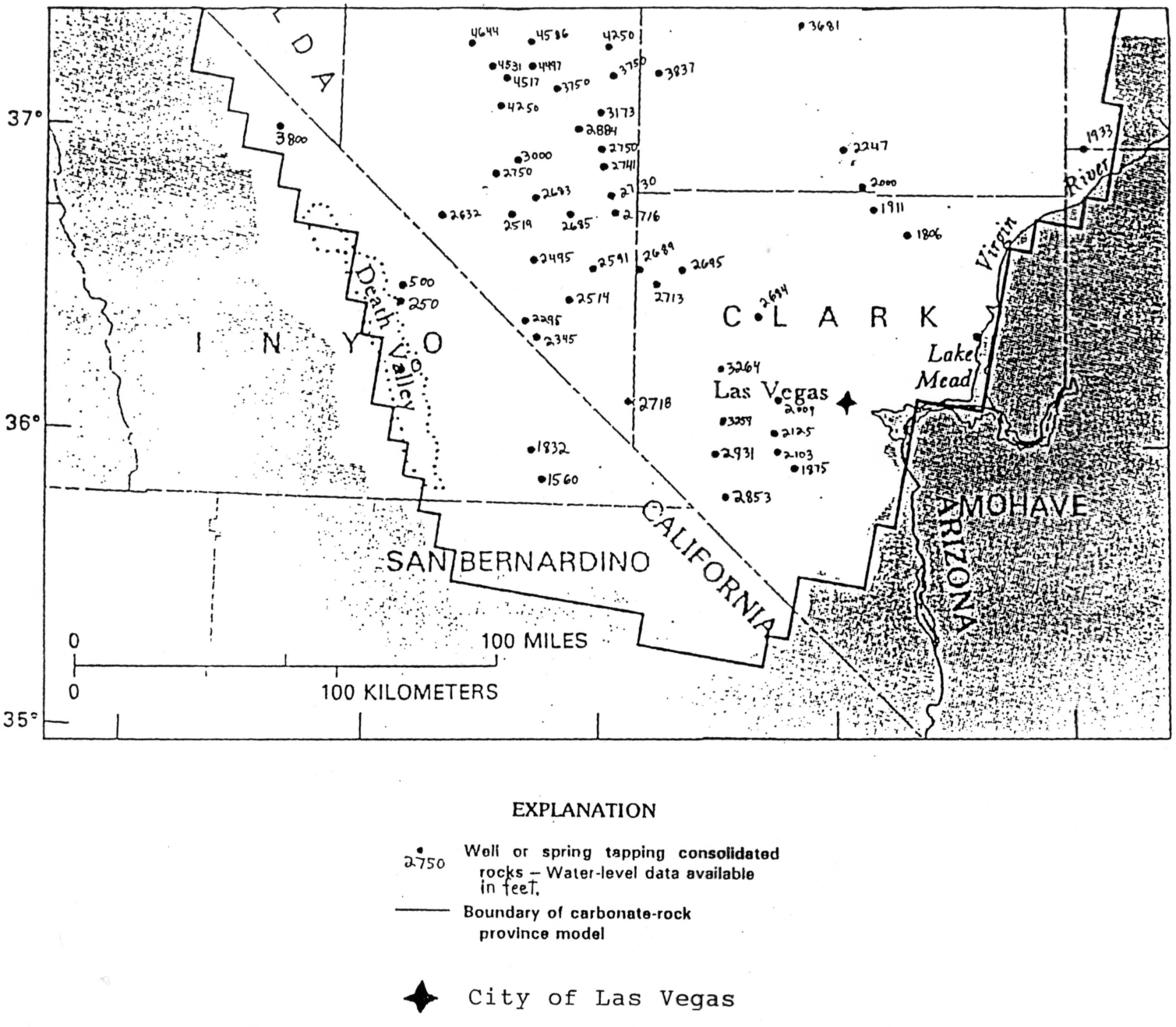
Figure 1.7
Rules for contouring. Source: AGI/NAGT, 1986, p. 71.

12) Is there a stagnation point on the potentiometric surface in Figure 1.8? If so, approximately where is it located? Label this spot on your map.

13) Examine Figure 1.9 on page 11 and compare it to Figure 1.8. Where do you think the aquifer is being recharged?

14) How are these recharge areas evident on your potentiometric surface?

Groundwater Flow



EXPLANATION

2750 Well or spring tapping consolidated rocks – Water-level data available in feet.

Boundary of carbonate-rock province model

City of Las Vegas

Figure 1.8

Potentiometric data for wells tapping bedrock in the Carbonate-Rock Province of The Great Basin. Source: Burbey and Prudic, 1991, p. D33, U.S.G.S. Professional Paper 1409-D.

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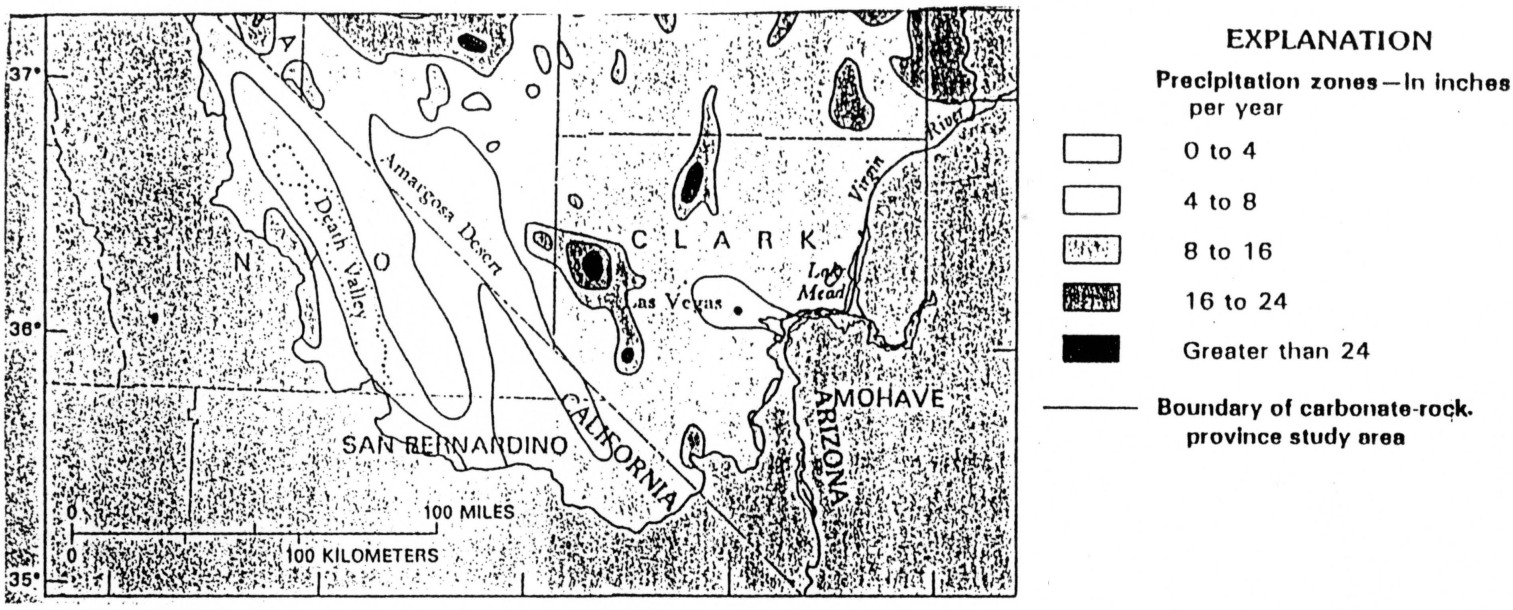

Figure 1.9
Annual precipitation in the Carbonate-Rock Province. Source: Burbey and Prudic, 1991, p. D8, U.S.G.S. Professional Paper 1409-D.

15) Where is there a major area of evaporation?

16) How is this area of evaporation evident on your potentiometric surface?

In 1856 a civil engineer named Henry Darcy published the results of an experiment in which he determined the principles of the flow of water through sand. He introduced a mathematical equation, now known as **Darcy's Law**, that allows one to calculate the volume of water that will flow through a given cross sectional area given a specified difference in hydraulic head. A slight modification of Darcy's Law allows one to calculate the **linear groundwater velocity**. This is the actual velocity at which water will move through an aquifer. The linear groundwater velocity may be calculated using the equation given on the next page.

Groundwater Flow

$$v = (K\ dh)/(n_e\ dl)$$

The terms are defined as follows:

v Average linear groundwater velocity. Units of length/time.
K Hydraulic conductivity. This is a proportionality coefficient that characterizes the aquifer's ability to transmit water. Units of length/time.
dl This is the length of the flow line over which the velocity is being calculated. Units of length.
dh This is the change in hydraulic head over the length **dl**. Units of length.
n_e This is the effective porosity of the aquifer. It is the volume of void spaces in an aquifer which can transmit water, divided by the total volume of the rock or sediment. Unitless.

17) Draw a flow line on your potentiometric surface map (Figure 1.8) from the **L** in Las Vegas to the center of the city of Las Vegas. Calculate how fast (in feet per day) the groundwater moves through the aquifer along this path using the equation for linear groundwater velocity. Assume the effective porosity is 0.025 and the hydraulic conductivity is 0.00000328 feet per second.

18) Assume you live in Las Vegas. One day a storm pours several inches of rain over the region and recharges the carbonate-rock aquifer. Will you ever get a chance to drink this storm water? Why or why not?

Groundwater Flow

Figure 1.10 depicts a well in a confined aquifer pumping a quantity of water, Q, out of the aquifer. As a result of the pumping a depression in the potentiometric surface is created around the well; this is called a **cone of depression**, because the depression is cone shaped as seen below. The groundwater flow direction is from left to right as indicated by the arrows on the far left and right hand sides of the diagram. However, within the **zone of influence** of the well the groundwater flows towards the well. This may be seen in the diagram in the area immediately to the right of the well where the water moves from right to left as indicated by the arrows; the direction of flow has been reversed in this area. Outside of the zone of influence the water does not feel the effect of the pumping well, and it continues to flow down gradient. Inside the zone of influence the hydraulic head is lowered, and the groundwater flows towards the pumping well.

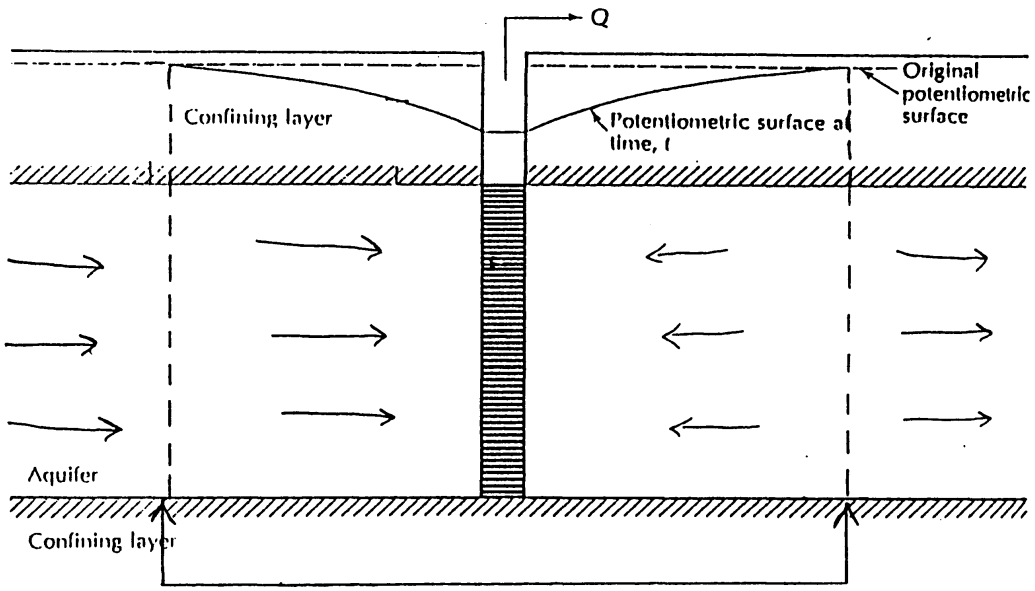

Figure 1.10
Cone of depression created by a pumping well. Source: Fetter, C. W., 1980, p. 164.

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19) The geologic cross section in Figure 1.11 below depicts a water table and equipotential lines. **H** represents equipotential lines with high hydraulic head, **L** represents equipotential lines with low hydraulic head. Draw flow lines on the cross section to illustrate the flow pattern.

20) Knowing that the water table parallels the topography of the land surface, what controls the flow pattern in Figure 1.11?

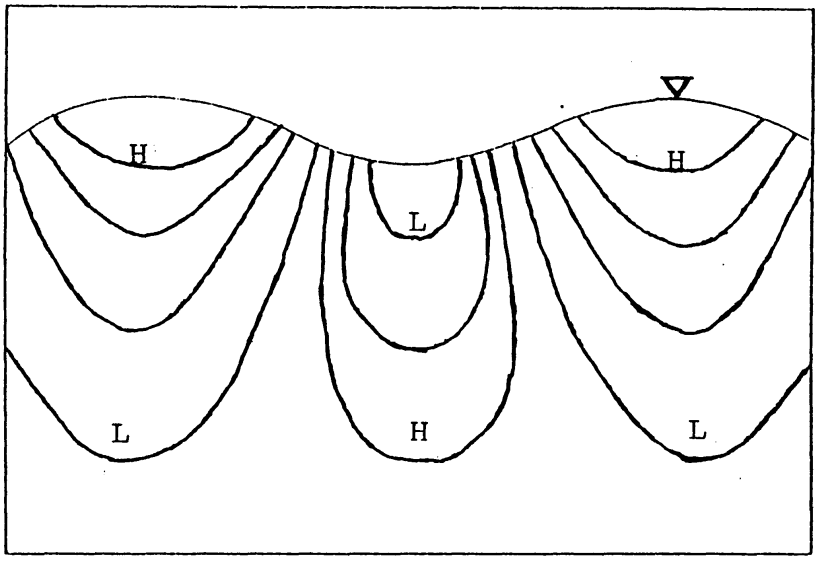


FIGURE 1.11

Geologic cross section showing water table and equipotential lines. Source: Hubbert, M. K., 1940, pp. 795-944.

21) Figure 1.12 on the following page shows a geologic cross section with two aquifers that have hydraulic conductivities (K) equal to 100 and which are separated by a confining layer with K=1. Draw a single flow line beginning at point **A** that will show the flow of water through the sloping confining layer. Note that the dashed lines are equipotential lines. Assume point **A** is located in an area of high hydraulic head and point **B** is in an area of low hydraulic head.

Groundwater Flow

22) Through which aquifer in the cross section in Figure 1.12 will the groundwater travel at the greatest velocity? Is it the aquifer on the left or the right? Assume both aquifers have the same effective porosity. Your answer should be based on the ratio dh/dl.

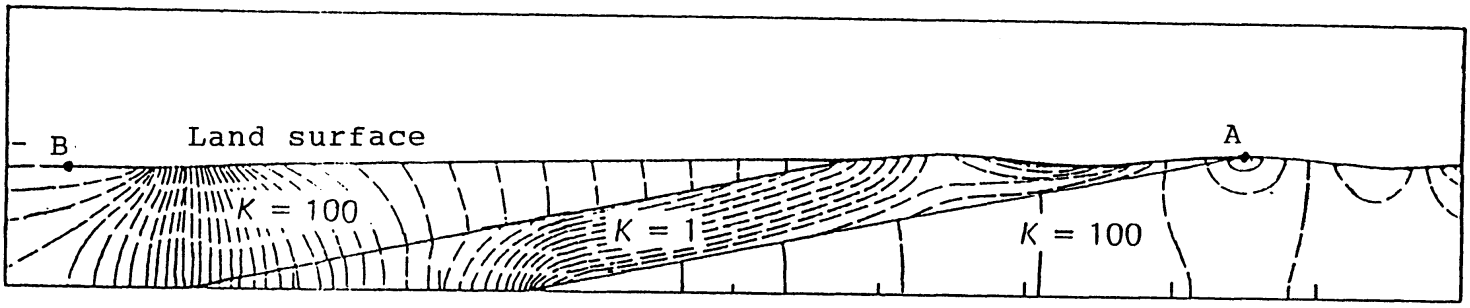


FIGURE 1.12
Cross section with sloping confining layer. Source: Freeze and Witherspoon, 1967, pp. 623-34.

23) Figure 1.13 depicts a geologic cross section with several highly permeable units. Draw flow lines beginning at points **A** through **E** to show the flow pattern of this cross section and to illustrate the effect of highly permeable units on flow systems.

24) Examine the flow lines you drew for question 23 and describe the effect the highly permeable layers (K=100) have on them as seen in the difference between where the flow lines begin and end; and the routes they take.

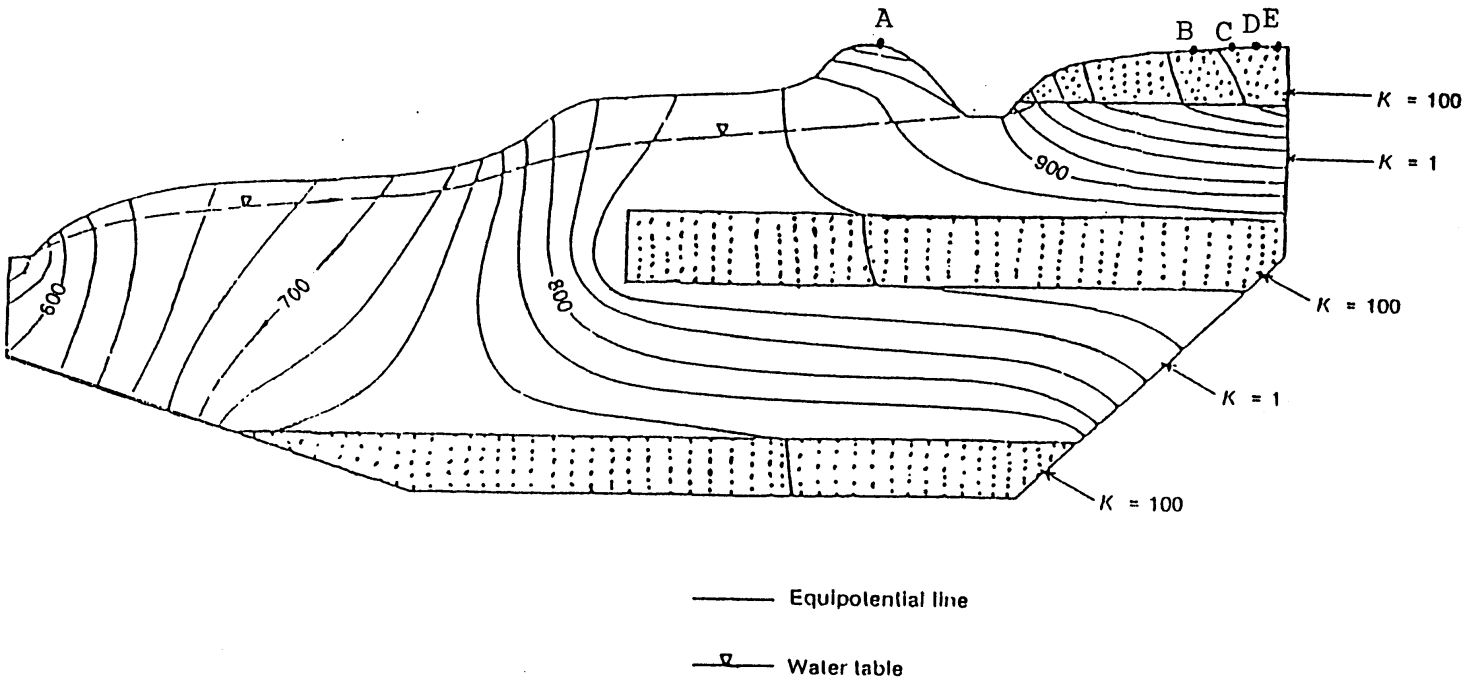


Figure 1.13
Cross section with highly permeable units. Source: Freeze, R. A., 1972.

Figure 1.14 on the next page depicts a drainage basin with a river and a potentiometric surface for a water table aquifer (unconfined aquifer). Examine the figure and answer questions 25 through 29 using the following information. In one part of the diagram the river recharges the water table; this occurs when the water table is below the river bottom and water moves from the river channel down through the soil towards the water table. When this happens the river is said to be a **losing stream**. In another part of the diagram the water table discharges into the river. This occurs when the water table is higher than the water level in the river. When this occurs the river is said to be a **gaining stream**; the river is gaining water from the aquifer below.

Groundwater Flow

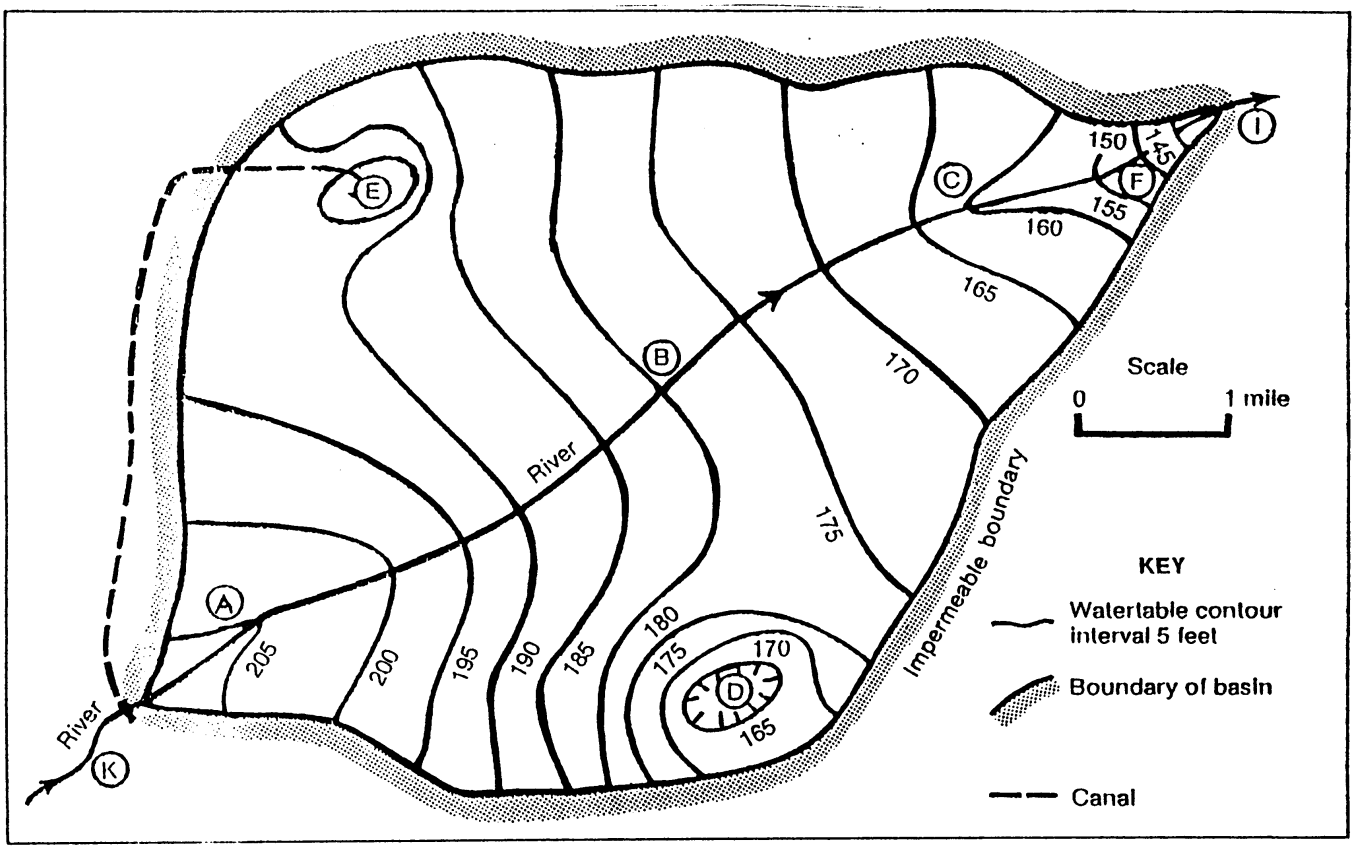


Figure 1.14
Drainage basin. Source: Davis and DeWiest, 1966.

25) At point **A** in Figure 1.14 does the river recharge the unconfined aquifer or does the aquifer discharge into the river? In other words, is the river a gaining or losing stream at this point? How can you tell?

26) Repeat question 25 for points **B** and **C**.

Groundwater Flow

27) There is a well located at point **D** in Figure 1.14; is the well pumping water into or out of the unconfined aquifer? How can you tell?

28) A canal connects points **K** and **E** as seen in the diagram. Draw flow lines from the end of the canal at point **E** that depict the direction the water will spread once it has infiltrated into the aquifer.

29) Although the canal diverts some of the river water to point **E**, does this affect the amount of water that flows in the river at point **I**? Why or why not? Assume there is no evaporation or transpiration taking place.

Figure 1.15 on the next page shows the groundwater withdrawals from Ordovician age aquifers in the Chicago and Minneapolis-St. Paul areas. Figure 1.16 shows the potentiometric surface of the ordovician aquifers (St. Peter-Prairie du Chen-Jordan aquifers) of the northern Midwest during the late 1800's. Study Figures 1.15 and 1.16 and answer the following question.

30) What affect would the dramatic increase in groundwater withdrawals from the late 1800's to 1980 in both urban areas have on the potentiometric surface and groundwater flow directions?

Compare the potentiometric surface from the late 1800's (Figure 1.16) to the one shown in Figure 1.17 for the year 1980 and answer questions 31 and 32.

31) Is your answer to question 30 correct for both Chicago and Minneapolis-St. Paul?

Groundwater Flow

32) Locate Des Moines, Columbia and Milwaukee on both of the potentiometric surfaces. Do these three cities have lower hydraulic heads or cones of depression around them in 1980 when compared to the late 1800's?

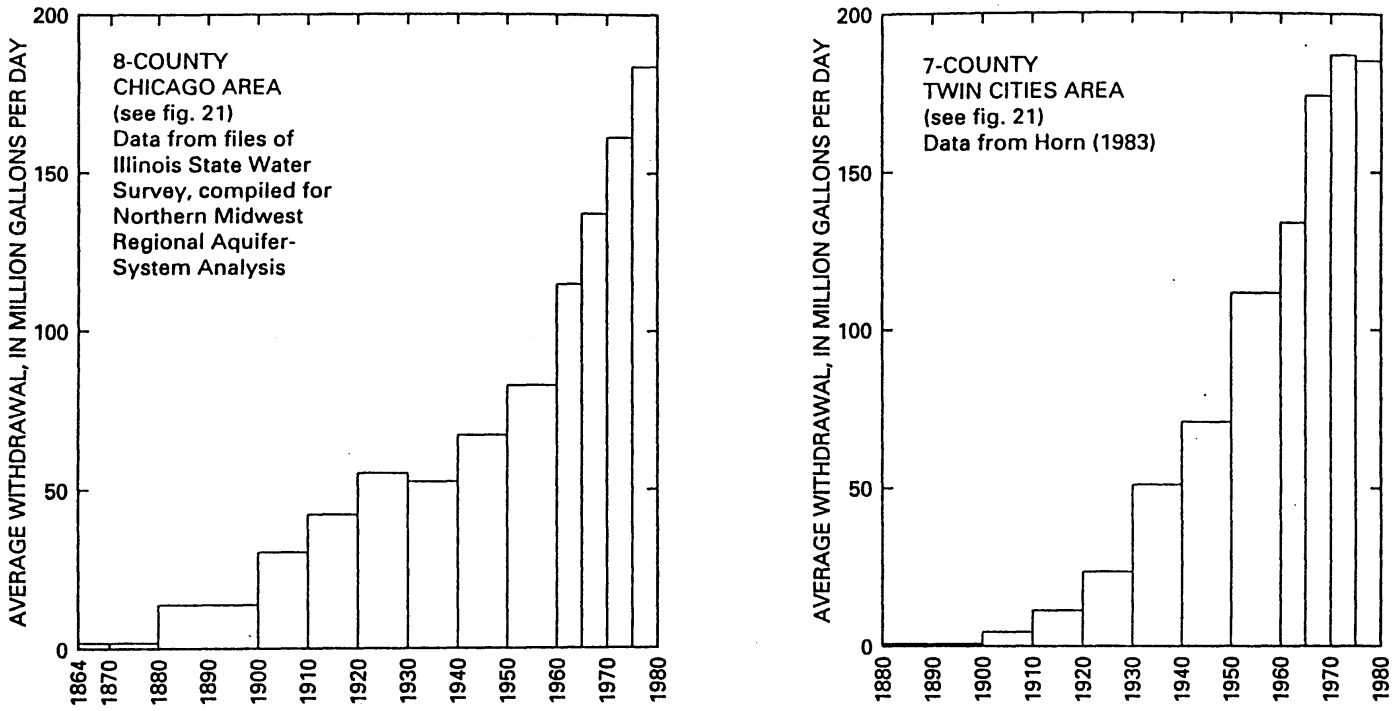


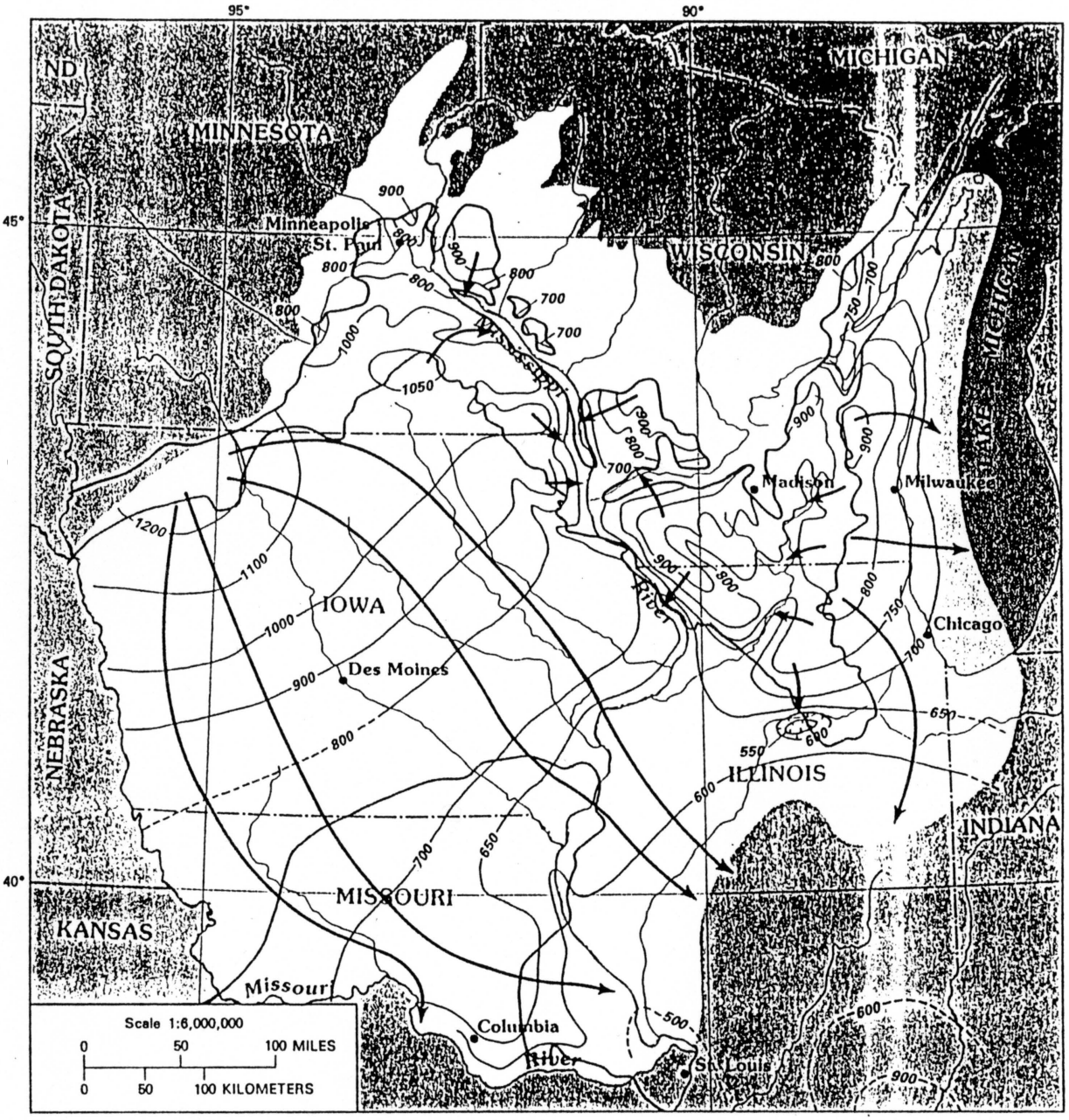
Figure 1.15
Groundwater withdrawals from the Ordovician aquifer system in the Chicago and Twin Cities areas, 1864-1980. Source: Young, H. L., U.S.G.S. Professional Paper 1405-A, p. A31.

Groundwater Flow

33) How come Minneapolis-St. Paul does not have a cone of depression around it, even though it withdrawals just as much water from the ordovician aquifers as does Chicago? Hint: The answer is on the geologic outcrop map in Figure 1.18.

34) Chicago pumps approximately 180 million gallons of water per day from the aquifer system, however the daily need for water is 2070 million gallons. Where does Chicago get the additional water?

Groundwater Flow



EXPLANATION

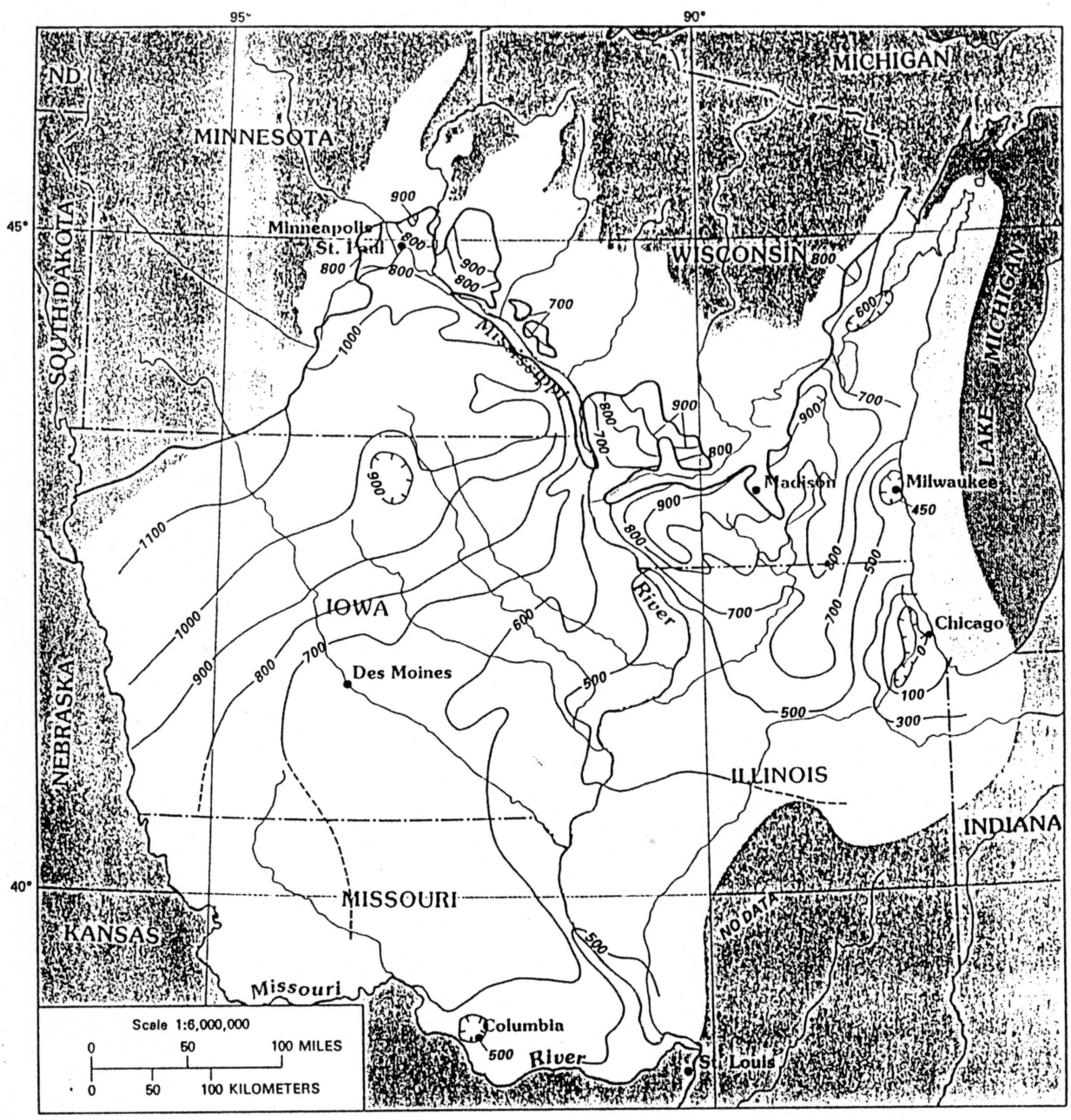
—500— POTENTIOMETRIC CONTOUR — Shows approximate altitude of the predevolpment potentiometric surface in the late 1800's for the St. Peter-Prairie du Chien-Jordan aquifer. Hachures indicate area of lower head. Dashed where inferred. Contour interval, in feet, is variable. Datum is sea level

→ GENERALIZED DIRECTION OF GROUND-WATER FLOW

Figure 1.16

Potentiometric surface of the Ordovician aquifer system for the northern Midwest during the late 1800's. Source: Young, H. L., U.S.G.S. Professional Paper 1405-A.

Groundwater Flow



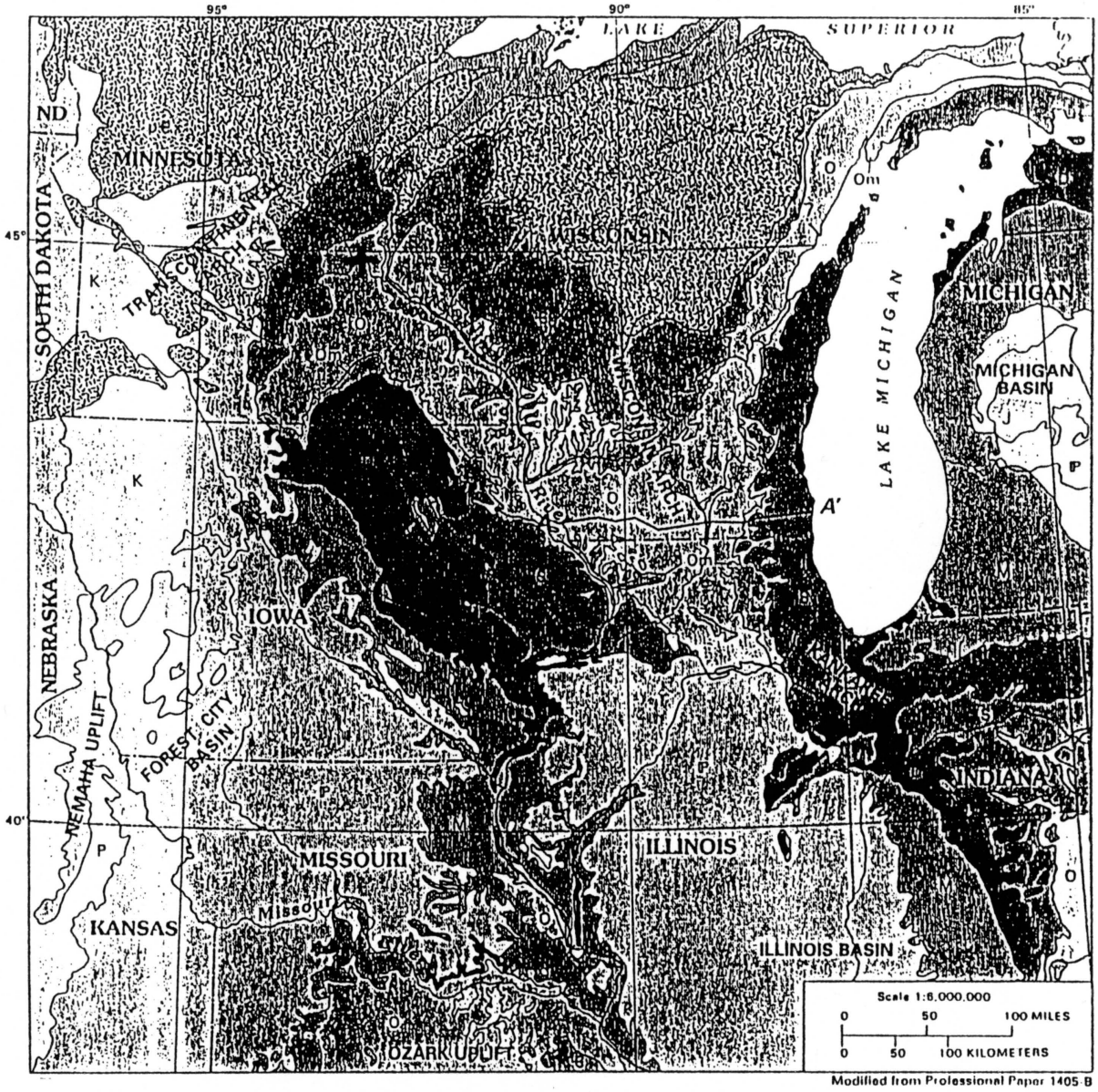
EXPLANATION

—500— POTENTIOMETRIC CONTOUR — Shows approximate altitude of the 1980 potentiometric surface for the St. Peter-Prairie du Chien-Jordan aquifer. Dashed where inferred. Hachures indicate area of lower head. Contour interval, in feet, is variable. Datum is sea level

Figure 1.17

Potentiometric surface of the Ordovician aquifer system for the northern Midwest during 1980. Source: Young, H. L., U.S.G.S. Professional Paper 1405-A.

Groundwater Flow



\+ Minneapolis-St. Paul area

FIGURE 1.18

General bedrock geology of the northern Midwest. Source: Young, H.L., U.S.G.S. Professional Paper 1405-A.

Groundwater Flow

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Answers To LAB 1

1) **A.** Precipitation
B. Infiltration
C. Groundwater flow
D. Overland flow
E. Runoff
F. Transpiration
G. Evaporation

2) **A.** Unsaturated zone
B. Capillary fringe
C. Water table
D. Saturated zone

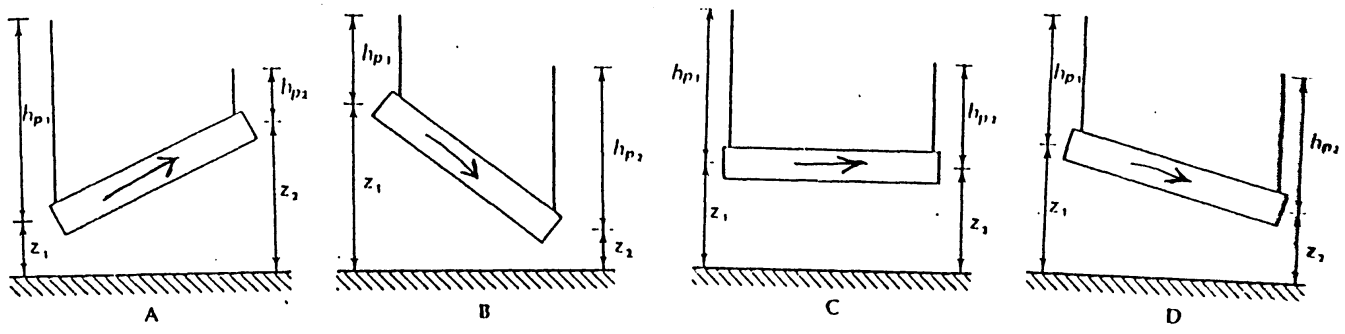
3) Recharge, runoff and infiltration.

4) **B.** Potentiometric surface
E. Flowing artesian well
F. Water table

5) The potentiometric surface (B) is for the confined portion of the aquifer. The water table (F) is for the unconfined portion of the aquifer.

6) One would expect to find springs or seepages at points **C** and **D**, because the water table intersects the land surface here, and the aquifer discharges here.

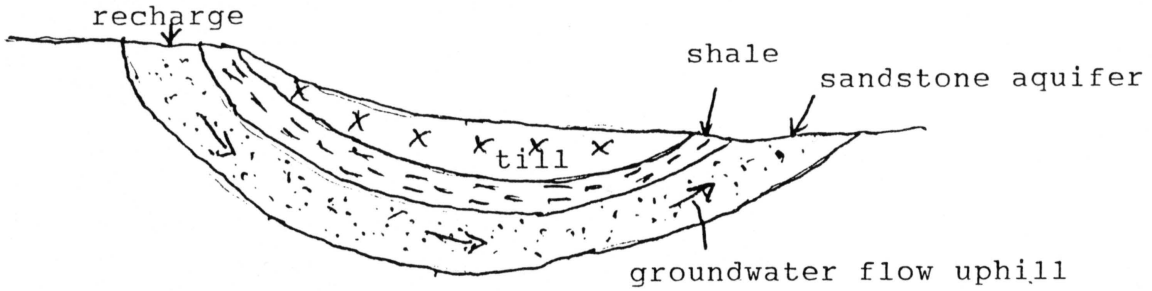
7)



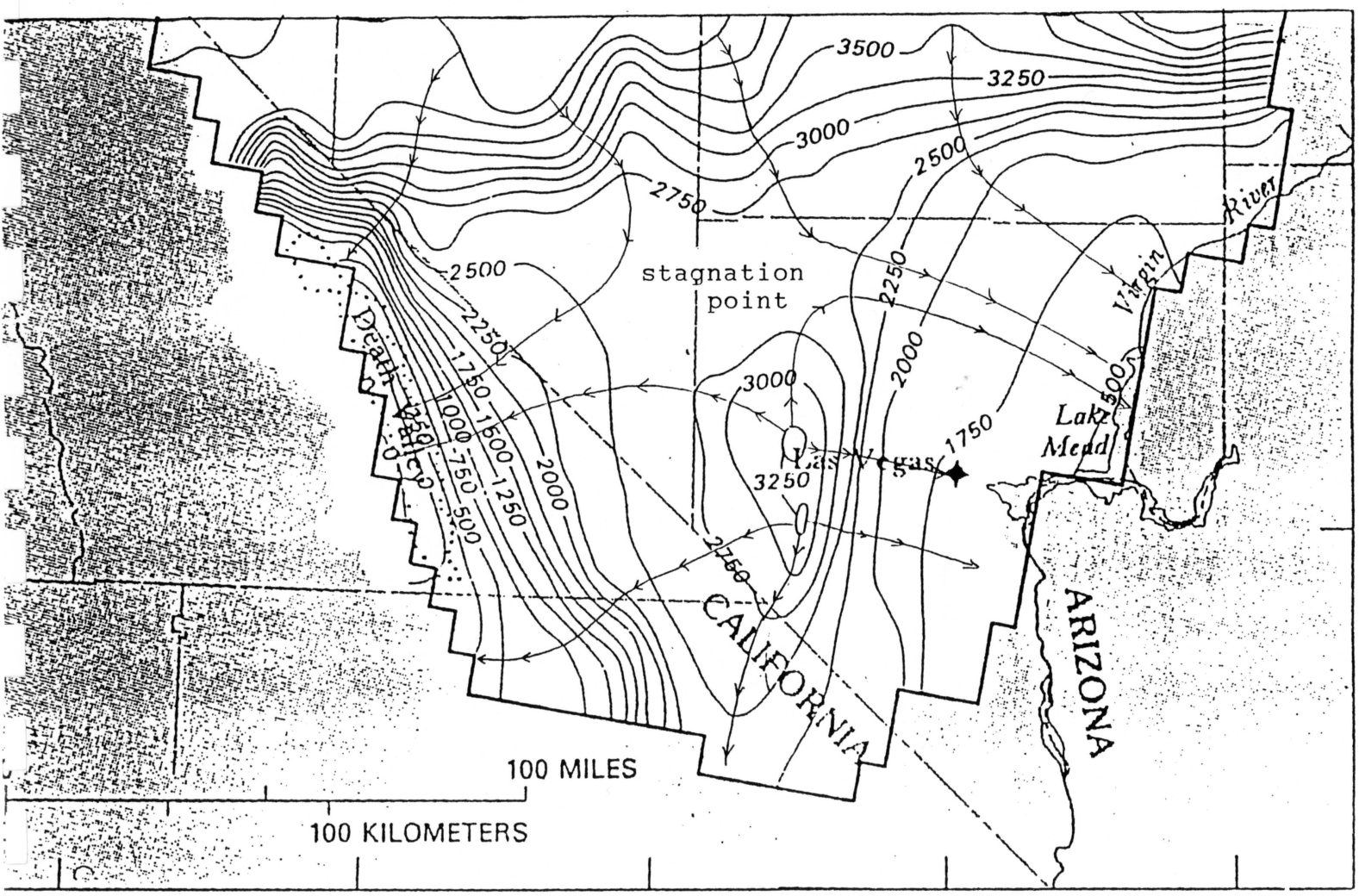
Answers To LAB 1

8) The water is flowing uphill.

9)



10), 11)



Answers To LAB 1

12) Yes, there is a stagnation point on the potentiometric surface located approximately in the center of the map.

13) The aquifer is being recharged in Clark County approximately 40 miles north and 40 miles west of Las Vegas.

14) These recharge areas have all their flow lines radiating outward, so water enters the aquifer here and moves laterally through the aquifer in all directions.

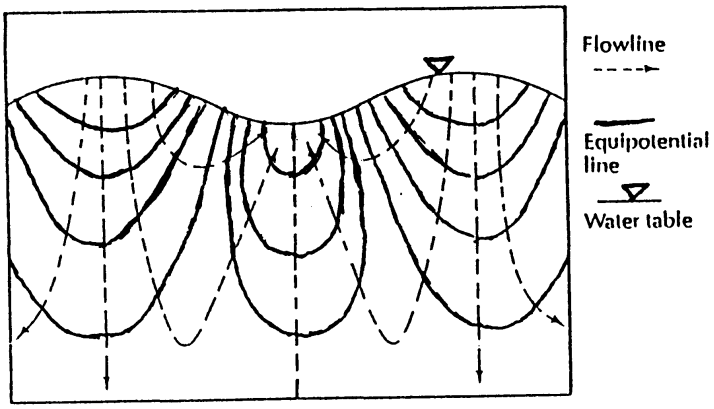
15) Death Valley.

16) The water level in the aquifer drops to zero indicating that all the water has evaporated.

17) dl = 30 miles = 158,400 feet
dh = 3250 feet - 1700 feet = 1550 feet
n_e = 0.025
K = 0.00000328 feet per second
v = (0.00000328)(1550)/(0.025)(158,400) = 0.0000013 ft/sec
convert to feet per day:
v = (0.0000013ft/sec)(60sec/min)(60min/hr)(24hr/day) = 0.11 ft/day

18) t = d/v = 158,400/0.11 = 1,440,000 days = 3945 years.
No, you will never get a chance to drink this water, because it will take 3945 years to travel from the recharge area to Las Vegas.

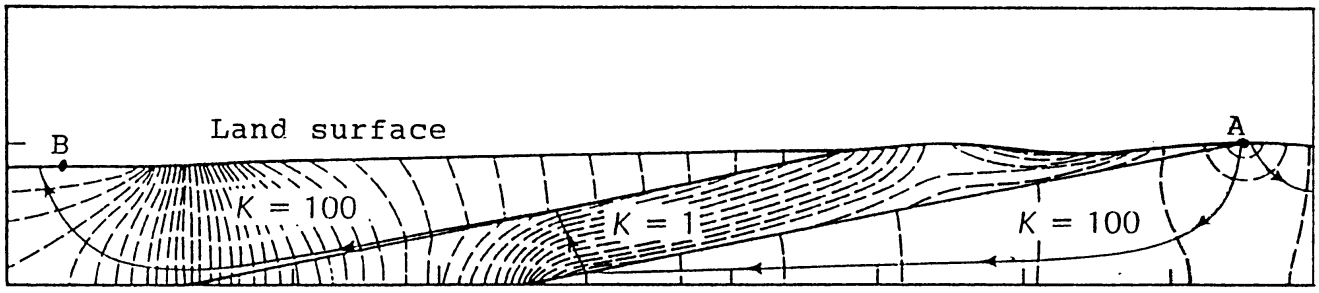
19)



Answers To LAB 1

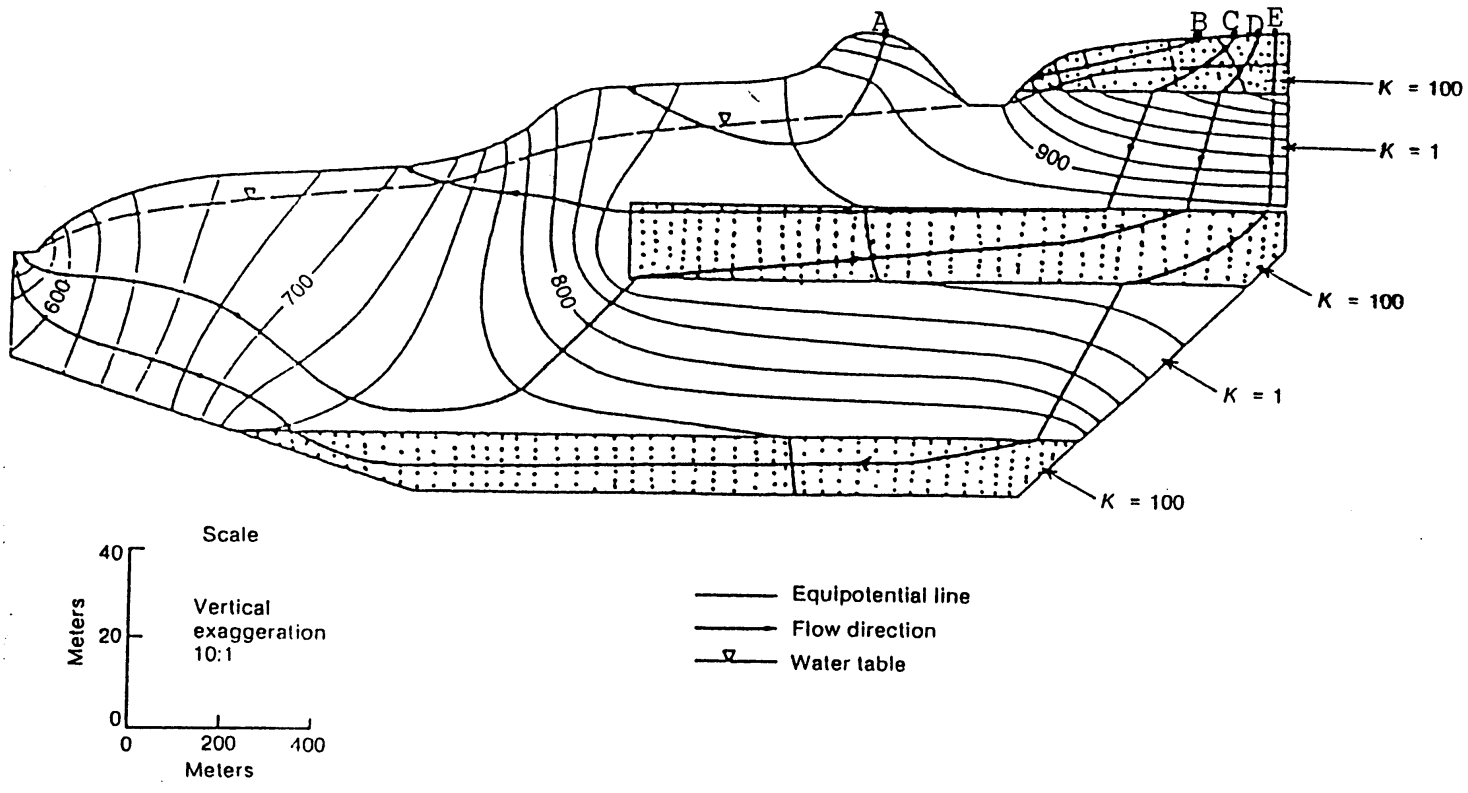
20) The topography of the land surface controls the flow pattern.

21)



22) The aquifer on the left has the largest ratio of dh/dl, so water will travel with the greatest velocity through it.

23)



Answers To LAB 1

24) The flow lines **B** through **D** start at approximately the same location and end up in very different spots. Flow lines **D** and **E** start next to each other, travel through different highly permeable units, and end up in the same location. The highly permeable units attract flow lines.

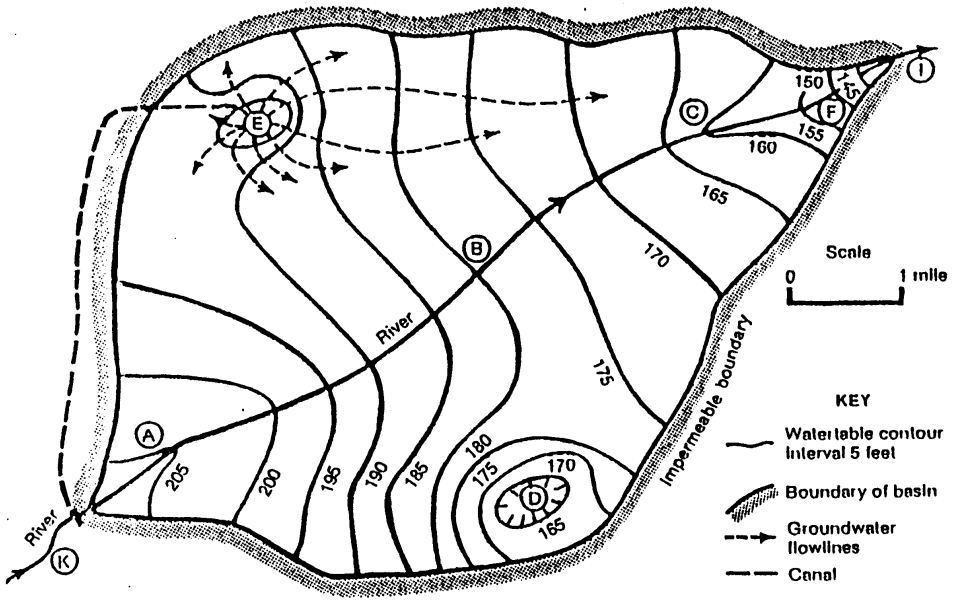
25) The river recharges the aquifer because the hydraulic head at point **A** is higher in the river than in the adjacent aquifer. A flow line beginning at point **A** will point away from the stream, thus water is moving from the stream into the aquifer. The river is a losing stream at this point.

26) At point **B** neither recharge or discharge occurs because the hydraulic head in the river is the same as in the aquifer.

At point **C** the aquifer discharges into the river because the hydraulic head in the aquifer is higher than the water level in the river. A flow line beginning at point **C** will point towards the river, thus water is moving from the aquifer into the stream. The river is a gaining stream at this point.

27) The well is pumping water out of the aquifer because the hydraulic heads get lower around the well, creating a cone of depression.

28)



Answers To LAB 1

29) No, it does not affect the amount of water flowing in the river at point I. All the water diverted to point **E** will flow back inot the river or into the aquifer and discharge back into the river. No water is lost to the outside of the basin.

30) The increase in groundwater withdrawal will lower the hydraulic head around the cities, creating a cone of depression around each city. One would also expect to see a change in the groundwater flow directions around the cities.

31) For the Chicago area: Yes, there is a cone of depression around the city. Thus, the hydraulic head has been lowered and the natural groundwater flow direction has been altered.

For the Twin Cities area: No, there has been no change in hydraulic head or flow direction.

32) Yes. Des Moines has a lower hydraulic head, and Columbia and Milwaukee both have prominent cones of depression around them.

33) The Ordovician rocks (aquifer) outcrops at the land surface around the Twin Cities, so the aquifer is unconfined here. Therefore, the aquifer gets recharged here and heavy groundwater withdrawal has minimal effect on the potentiometric surface. Also, the river adjacent to the area will recharge the aquifer, further reducing the effects of pumping on the potentiometric surface.

34) Lake Michigan.

LAB 2

Contaminant Flow Exercise

Objective The purpose of this laboratory exercise is to introduce the basic concepts of contaminant movement in groundwater and to use these concepts to solve contaminant flow problems.

Introduction Because water is such a valuable natural resource, it is essential to study and understand the many ways water may be polluted. Toxic waste spills, leaking storage tanks, leaking landfills and unsafe waste disposal practices are several ways in which subsurface water may become contaminated. The types of pollutants vary widely and may include carcinogens, hydrocarbons, heavy metals, microorganisms and radionuclides. The results of these contaminants can destroy the environment and cause sickness and disease in ourselves and future generations. If one can comprehend the processes that affect contaminants in groundwater and understand their movement and behavior then one may predict the fate of a contaminant, suggest methods to clean up the pollutant and prevent future contamination.

Contaminants dissolved in water in the saturated zone will move in the same direction as the groundwater. The dissolved contaminant particles are suspended in solution and flow along with the water; this process is known as **advection**. As a contaminant moves through the subsurface it spreads vertically and horizontally to form a **plume**. Figure 2.1 on the next page displays two types of contaminant plumes in map view; the first, shown in **A**, is a plume created by a single source that continually leaks a contaminant into the groundwater, and as time passes the plume gets larger and larger. The second, shown in **B**, depicts a plume created by a one time spill (a slug). At time t_o the spill is small, but later at times t_1, t_2 and t_3 the plume has moved down gradient in the direction of groundwater flow, and it has spread horizontally.

Figure 2.2 on the next page shows a contaminant plume in longitudinal cross section which was produced by a continuous source. The top diagram depicts the plume at some early time and shows the concentrations of the contaminant. Note that the concentration (given by the value on the isoline and which is usually referred to as a concentration contour) is higher close

to the source and less at the tip of the plume farthest from the source. At a later time, shown in the bottom diagram of Figure 2.2 the concentration of the contaminant near the continuous source is the same, but the leading edge of the plume has moved down gradient and the contours for the lesser concentrations have stretched down gradient with the tip of the plume.

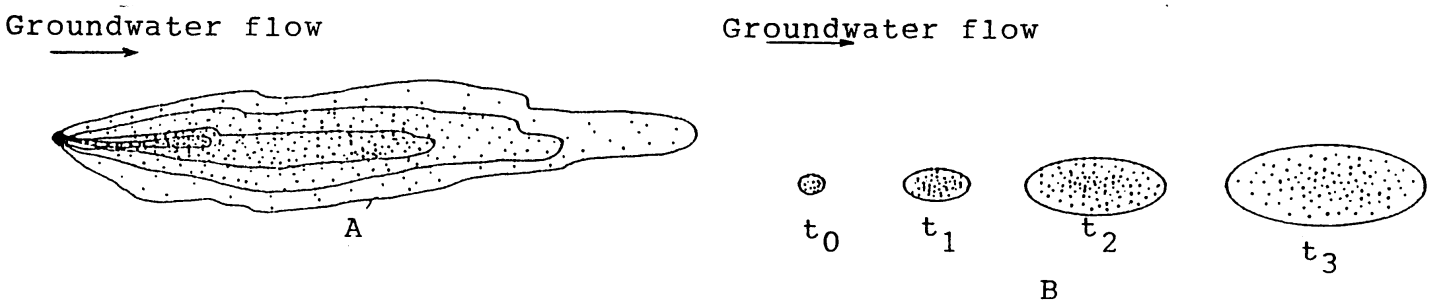


FIGURE 2.1
Contaminant plumes in map view. **A** is from a continuous source; **B** is from a one-time source. Stippling represents relative concentration of the contaminant. Source: Fetter, C. W., 1980, p. 395.

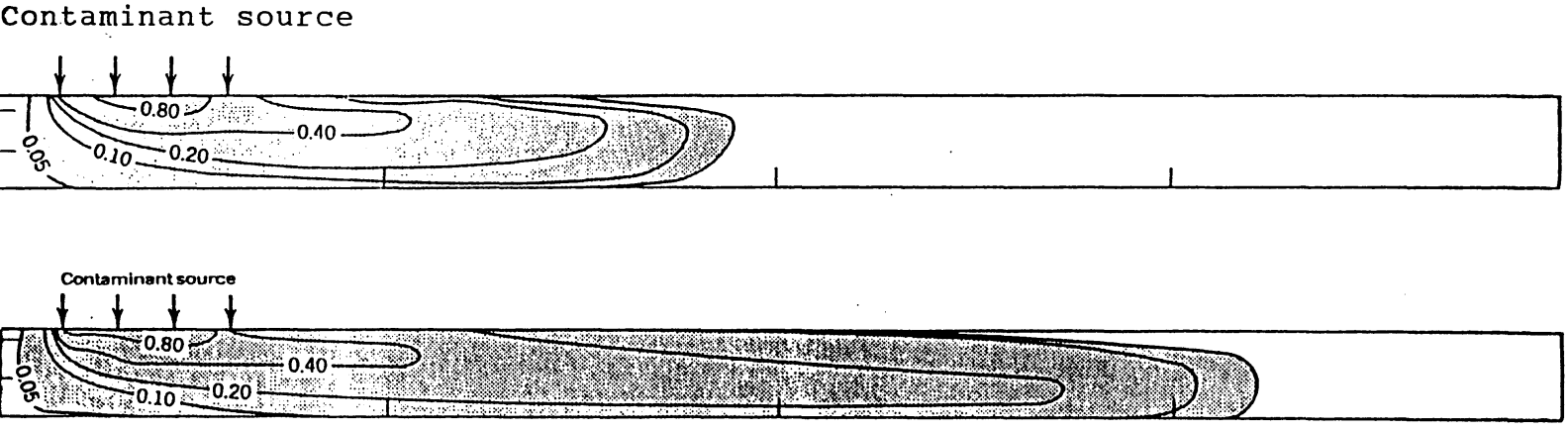


FIGURE 2.2
Contaminant plumes in cross section. Contours represent relative concentrations of the contaminant. Source: Schwartz, F. W., 1975, pp. 51-71.

Contaminant Flow

The process by which a contaminant dissolved in water mixes with uncontaminated water is called **dispersion**. Dispersion is caused by the difference in velocity between the dissolved contaminant and the uncontaminated water as they travel through pore spaces and through various geologic units. The effect of dispersion is to spread the contaminant vertically and horizontally as it moves through an aquifer, thus reducing it's concentration. This effect can be seen in the plumes depicted in Figures 2.1 and 2.2. Dispersion is discussed further in the introduction to question 11.

Another process which affects the movement of a contaminant is **diffusion**. Diffusion is the process by which ions or molecules dissolved in water move from an area of high concentration to an area of lower concentration. Diffusion is a very slow process compared to advection and dispersion, and it usually does not account for any significant contaminant movement unless the rate of advection is very slow.

An important process that affects many contaminants is **adsorption**. This is the process in which dissolved contaminant particles attach themselves to mineral surfaces in the aquifer, thus leaving the dissolved stage. This is caused by the **hydrophobic** (water fearing) character of most organic compounds. These compounds would rather cling to surfaces on the aquifer than be dissolved in the groundwater. The result of adsorption is that the contaminant will move slower through the aquifer than the surrounding water. When a contaminant moves slower as a result of adsorption, it's movement is said to be **retarded** with respect to the groundwater flow. The degree to which a contaminant is retarded can be quantified using a **retardation factor (R_f)**. The retardation factor can be easily calculated using the equation given below.

$$R_f = \text{velocity of water/velocity of contaminant}$$

Note that $R_f \geq 1$ since the velocity of a contaminant is always less than or equal to the velocity of the groundwater.

Contaminants are also affected by **chemical reactions** as they move through the subsurface. As a contaminant moves underground the pH (acidity)

of the groundwater may change. An increase in pH may cause certain metal ions (Na+, Fe++ for example) to dissolve out of the aquifer and into the groundwater. On the other hand, a decrease in pH will have the opposite affect; metal ions may adsorb to mineral surfaces in the aquifer. In either case the chemical composition of the groundwater will change. One specific chemical reaction in groundwater which will change the pH of the water involves hydrochloric acid (HCl) and limestone (the chief component in limestone is CaCO3). This reaction is written as follows:

$$HCl + CaCO_3 \rightarrow Ca^{2+} + HCO_3^- + Cl^-$$

The result of this reaction is the neutralization of HCl, which raises the pH of the groundwater. Thus, the concentration of hydrochloric acid is decreased.

Another interesting process that affects the movement of contaminants is **biotransformation**. This is the process where organic compounds are utilized as food by bacteria or other microorganisms that live in an aquifer. The microorganisms oxidize the organic compounds, and the compounds are broken down into CO2 and H2O. The process of biotransformation starts slowly as bacteria acclimate themselves to a particular contaminant; this may take several weeks. However, once the bacteria are acclimated they may entirely consume a contaminant. Because of this, biotransformation holds great promise as a method of cleaning up organic spills.

Finally, **radioactive decay** will affect the migration of any contaminants that are radionuclides. Because radioactive elements decay (some very rapidly), they have a half-life which must be taken into account when trying to determine their concentrations and plume behavior.

Figure 2.3 on the next page depicts plumes of chloride (CL), carbon tetrachloride (CTET) and tetrachloroethylene (PCE) at various times. These plumes were created as part of an experiment performed at Borden, Ontario. The experiment was in a shallow sand aquifer in an inactive sand quarry. The site was carefully analyzed before any contaminants were released in order to quantify the geology and hydrology of the area. The contaminants were then introduced into the aquifer and observed using a series of wells in the aquifer over a period of several years. Examine the plumes in Figure 2.3 and

Contaminant Flow

answer the following five questions.

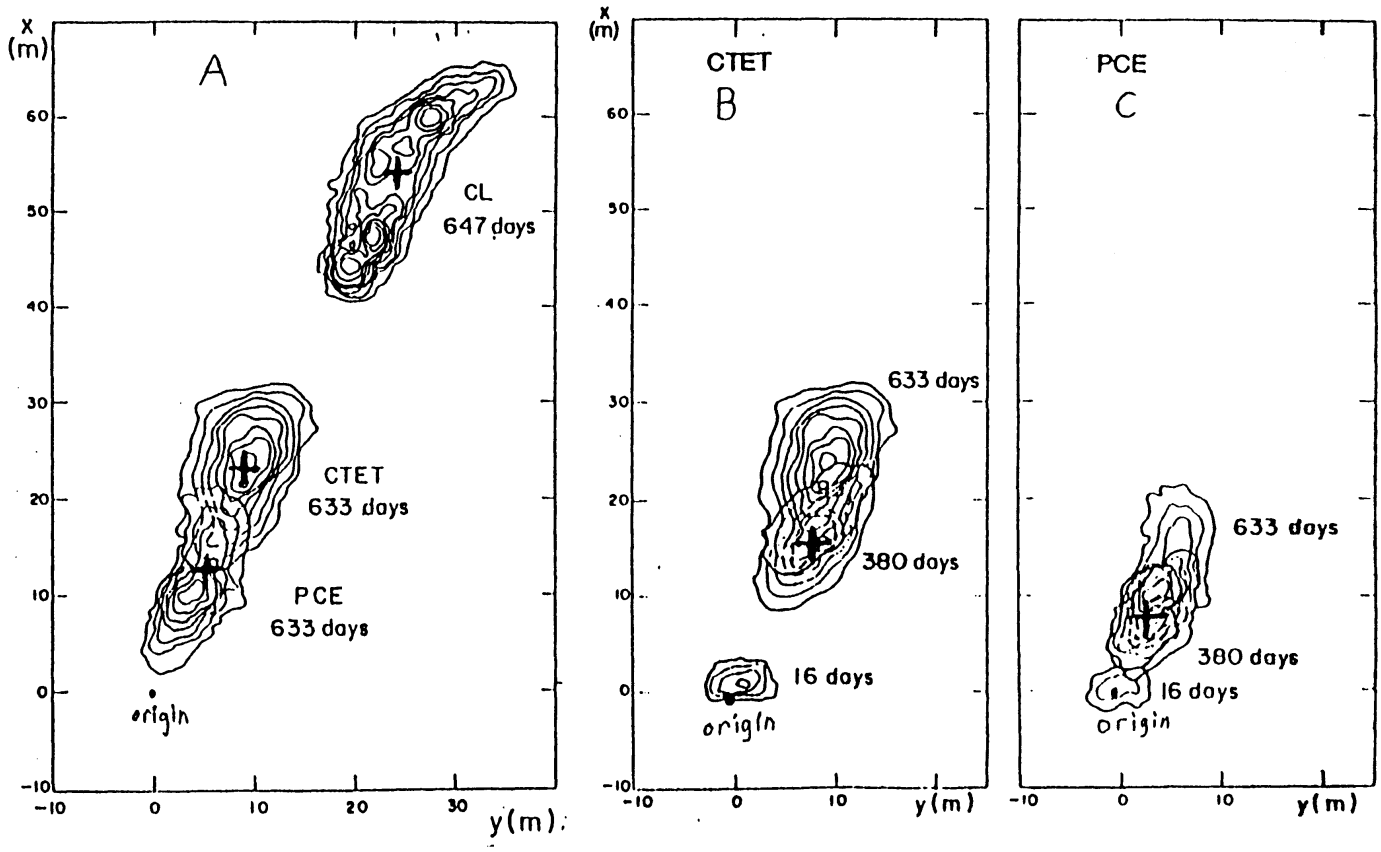


Figure 2.3

CL (A), CTET (B) and PCE (C) plumes at the Borden, Ontario experimental site after 16, 380, 633 and 647 days. Plume depth below surface averaged from 1.5 to 7.5 meters. + = center of mass ; - concentration contour. Source: Roberts, Goltz and MacKay, 1986, p. 2050.

1) Chloride is often used as a groundwater tracer because it is nonreactive and nonsorptive. It moves with the same velocity as the groundwater. Knowing this, calculate the groundwater velocity using the chloride tracer in diagram **A**. Use the relationship v = d/t and measure the distance from the origin to the center of mass of the plume.

Contaminant Flow

2) Using the same method as in question 1 calculate the velocity at which CTET and PCE are moving through the aquifer. Use diagram **B** and t = 380 days.

3) In questions 1 and 2 why is it appropriate to calculate the velocity using the equation v = d/t instead of using Darcy's equation for linear groundwater velocity?

4) What is the name of the process that causes CTET and PCE to move slower than CL through the aquifer? What is the cause of the process?

5) Calculate the retardation factor (R_f) for CTET and for PCE.

6) If R_f and the initial amount of contaminant are known, then one may calculate the amount of contaminant that is still dissolved in the groundwater using the following relationship:

Mass of dissolved contaminant in solution = Initial mass of contaminant/Rf

Calculate the amount of CTET and PCE that are still dissolved in the groundwater using the data in Figure 2.4 on the next page.

Contaminant Flow

Estimated Total Mass of Organic Compounds

Elapsed Time, days	Mass, g				
	CTET	BROM	PCE	DCB	HCE
Initial*	0.37	0.38	0.36	4.0	0.23
16	0.34	0.51	missing data	4.4	0.16
29	0.47	0.50	0.47	4.7	0.17
43	0.58	0.55	0.44	5.4	0.15
63	0.40	0.46	0.40	5.2	0.05
85	0.35	0.34	0.42	2.0	0.07
330	0.33	0.26	0.36	1.4	bdl
380	0.36	0.24	0.42	1.7	bdl
407	0.43	0.21	0.37	1.1	bdl
633	0.25	0.08	0.35	0.4	bdl
709	0.30	0.08	0.48	0.5	bdl

Bdl, below detection limit.
*Known mass introduced into injection system.

Figure 2.4
Table of estimated total mass of organic compounds at the Borden, Ontario site. Source: Roberts, Goltz and MacKay, 1986, p. 2050.

7) Calculate R_f for CTET and PCE at 633 days and compare these values to the ones obtained for 380 days.

8) Calculate the amounts of CTET and PCE still dissolved in water after 633 days and compare to your answer for 380 days.

9) Examine the data for HCE in Figure 2.5. What process would cause the loss of HCE in solution within the first 43 days?

Sampling Day	Mass, g				
	CTET	BROM	PCE	DCB	HCE
Initial*	0.37	0.38	0.36	4.0	0.23
1	0.15	0.17	not reported†	not reported†	not reported†
9	0.22	0.25	not reported†	0.69	0.03
16	0.19	0.27	not reported†	1.10	0.030
29	0.25	0.25	0.15	1.03	0.028
43	0.30	0.26	0.13	1.09	0.022
63	0.20	0.21	0.11	0.96	0.007
85	0.17	0.15	0.11	0.35	0.008
330	0.14	0.10	0.07	0.18	bdl
380	0.15	0.09	0.08	0.21	bdl
407	0.18	0.08	0.07	0.14	bdl
633	0.10	0.03	0.06	0.04	bdl
709	0.12	0.03	0.08	0.05	bdl

FIGURE 2.5
Mass of organic compounds in solution versus time. Source: Roberts, Goltz and MacKay, 1986, p. 2051.

10) What process would cause the sudden large loss of HCE between 43 and 63 days and eventually cause the disappearance of HCE?

As described above, dispersion will cause vertical and horizontal spreading of a contaminant. The different directions of spreading are given separate names. Spreading in the direction of groundwater flow is referred to as **longitudinal dispersion**. The dispersion perpendicular to the direction of groundwater flow is called **horizontal transverse dispersion**, and the dispersion in the up-and-down direction is termed

Contaminant Flow

vertical transverse dispersion. Transverse dispersion is often called lateral dispersion. Figure 2.6 below and Figure 2.7 on the next page help to illustrate the causes of longitudinal and transverse dispersion.

Longitudinal dispersion may be quantified using the following formula:

$$D_L = (a_L)(v)$$

D_L = coefficient of longitudinal dispersion. Units of length squared/time.
a_L = dispersivity. This is a proportionality coefficient that quantifies the dispersive characteristics of the aquifer. Units of length.
v = linear groundwater velocity. Units of length/time.

The two transverse dispersions may be calculated in a manner similar to D_L using : $D_T = (a_T)(v)$.

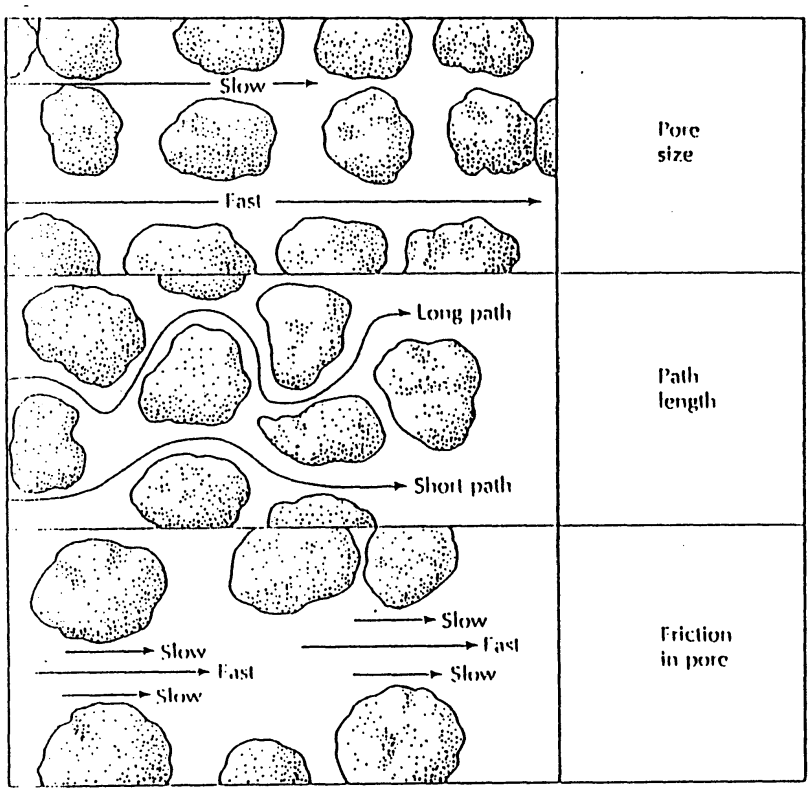


FIGURE 2.6
Factors causing longitudinal dispersion. Source: Fetter, C. W., 1980, p. 392.

Contaminant Flow

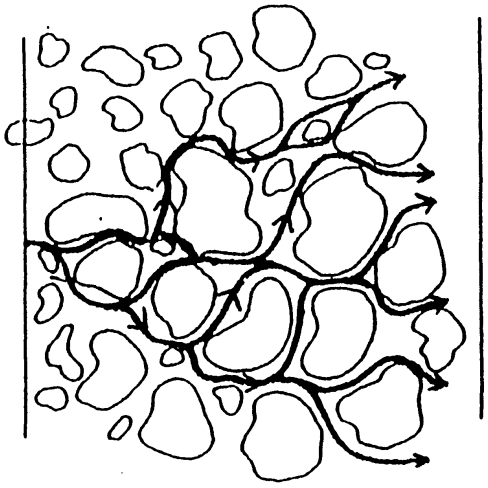


FIGURE 2.7

Flow paths which cause lateral dispersion. Source: Fetter, C. W., 1980, p.393.

Figure 2.8 below depicts a chloride plume at the Borden, Ontario site. This plume was produced from a slug injected in the sand aquifer. Notice the plume has an elliptical shape. One can make use of the simple geometry of the plume to calculate the coefficients of dispersion and dispersivity.

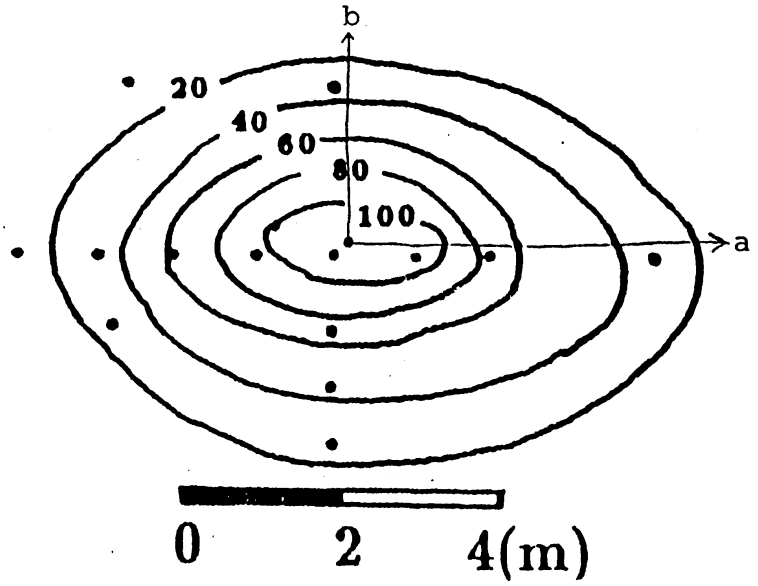


FIGURE 2.8

Chloride plume, after 121 days, resulting from a slug injection at the Borden site. Source: Jiao, J. J., 1993, pp. 57-59, after Sudicky et al. (1983).

Contaminant Flow

An ellipse is described by the length of it's major axis (a) and the length of it's minor axis (b). The area of an ellipse (A) may be calculated by: $A=\pi ab$.

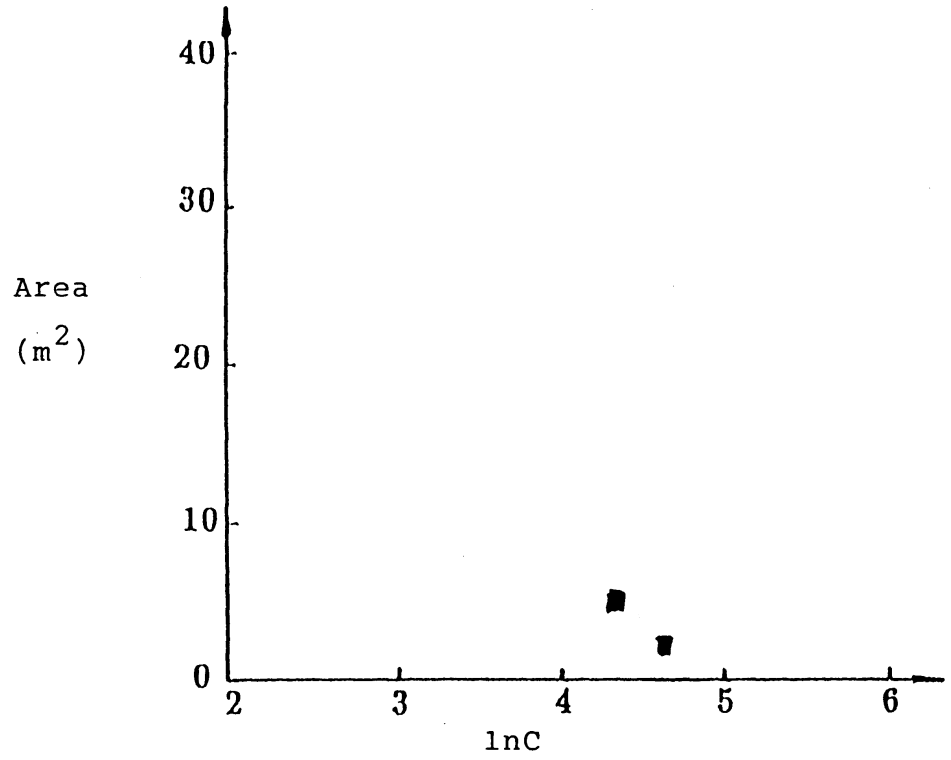
11) In order to calculate the coefficients of dispersion and dispersivity, fill in the table below as follows:
- For each concentration contour (C) measure the length of the major and minor axis and record these in the table.
- For each concentration contour calculate the ratio a/b and record these values in the table.
- Calculate the natural logarithm of each concentration contour and the area (A) of each ellipse created by the contours and record these values.

a/b	$C(mg/l)$	$a(m)$	$b(m)$	lnC	$A(m^2)$
	100				
	80				
	60				
	40				
	20				

12) On the graph on page 12 plot your values of area for the 20 and 40 concentration contours vs. the natural log of C for these contours. Some additional points are also provided. Draw a straight line through these points.

13) Determine the slope of the line you drew for question 12.

Contaminant Flow



Graph of A vs. lnC

14) Use the relationship $D_L D_T = [(-\text{slope})/(4\pi t)]^2$ to solve for the quantity $D_L D_T$.

15) Determine the average value for a/b from the data table above and use this average to calculate the ratio D_L/D_T using the relationship:

$D_L/D_T = (a/b)^2$

16) Use the results of questions 14 and 15 to determine the longitudinal and transverse dispersion coefficients (D_L and D_T).

Contaminant Flow

17) Calculate the longitudinal and transverse dispersivities. Let v = 0.25 meters/day.

18) By looking at the contoured plume in Figure 2.8 would you guess that the longitudinal or the transverse dispersion is greater?

19) Are your results from questions 16 and 17 consistent with your answer to question 18?

What is the effect of increasing transverse (horizontal or vertical) and longitudinal dispersion? An increase in transverse dispersion will make a plume wider or thicker. However, an increase in longitudinal dispersion will not make a plume longer; it will cause the contaminant to mix with an increased amount of uncontaminated water. This will cause the contaminant concentrations to decrease throughout the length of the plume. So, an increase in longitudinal dispersion simply results in lower contaminant concentrations and not a longer plume. Use this information to solve the following problems.

20) Given the contaminant plume in part **A** of Figure 2.9 on the next page, and knowing that it's vertical transverse dispersivity is 0.001 meters, draw the same plume in part **B** as it would appear if the vertical transverse dispersivity were 0.1 meters. As a hint the tip of the 0.5 concentration contour is provided (C/C_o = 0.5, or 50% of the original concentration of the contaminant).

21) Is the new plume thicker or thinner? Longer or shorter? Why?

Contaminant Flow

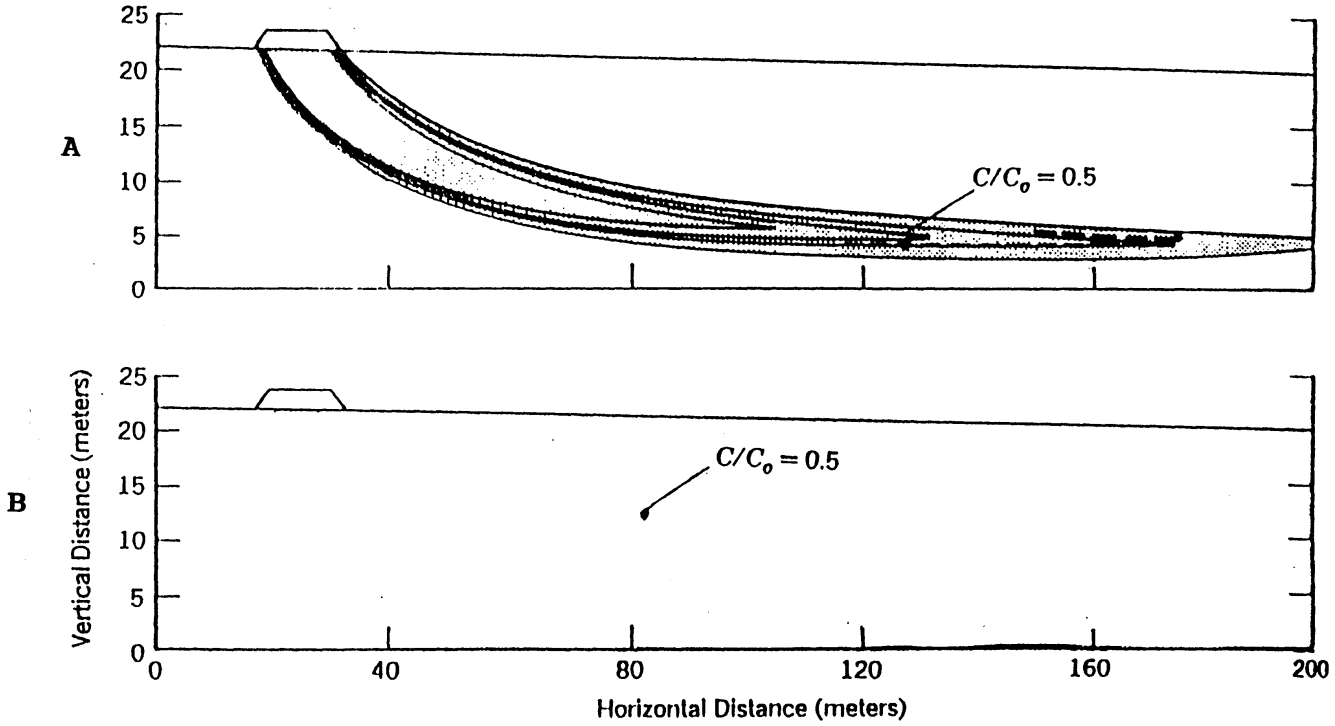


FIGURE 2.9

The effect of changing vertical transverse dispersivity; **A**, $a_{T=0.001}$ m; **B**, $a_{T=0.1}$ m. Contour interval is 0.25. Source: Frind and Germain, 1986, pp. 1857-73.

22) Part **A** of Figure 2.10 on the next page displays a contaminant plume with a given longitudinal and vertical dispersivity. Draw the plume in part **B** as it would appear if the dispersivities were changed as given.

23) How do the changes in longitudinal and vertical transverse dispersivity change the shape of the plume in part **B** of Figure 2.10?

Contaminant Flow

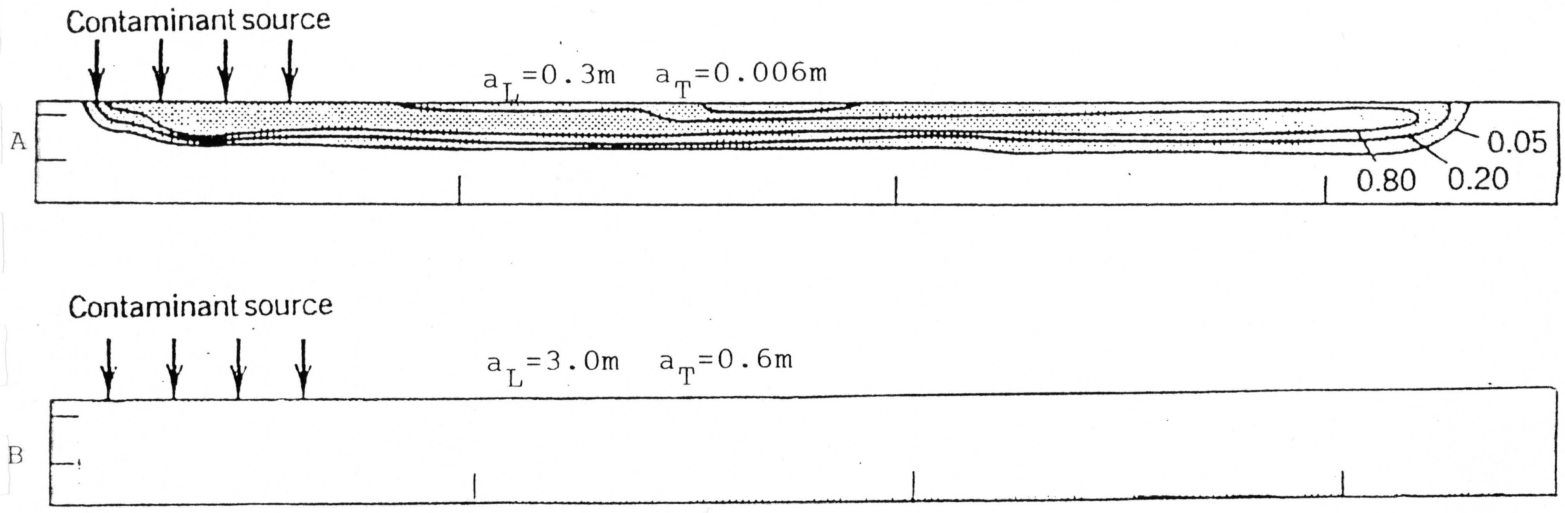
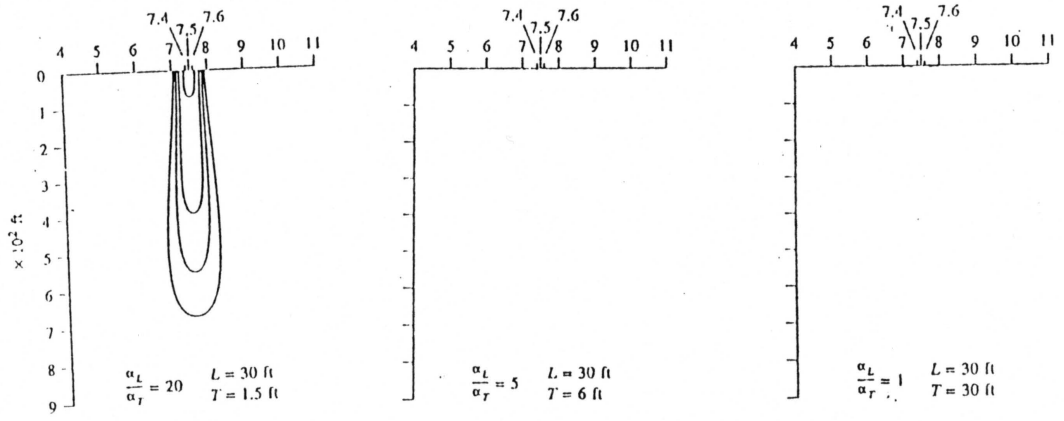


FIGURE 2.10

The effect of changing longitudinal and vertical dispersivities. Source: Schwartz, F. W., 1975, pp. 51-76.

24) Part **A** of Figure 2.11 below shows a contaminant plume with a longitudinal dispersivity of 30 feet and a horizontal transverse dispersivity of 1.5 feet. Draw the same plume in parts **B** and **C** changing the plume shape according to the dispersivities given.



A B C

FIGURE 2.11

The effects of changing longitudinal and horizontal dispersivity. Source: Fetter, C. W., 1993, p. 65.

Contaminant Flow

25) Does changing the horizontal transverse dispersivity affect the plume shape the same way changing the vertical dispersivity does?

Examine Figure 2.12 and answer questions 26 through 28.

26) Draw appropriate flow lines from points **A** and **B** that will show the direction of groundwater flow. Sketch in the plume of contaminant that would leak from the disposal area. Assume that the only process acting on the dissolved contaminants is advection; there is no adsorpton, dispersion, etc.... Also assume the three wells are not pumping hard enough to affect the groundwater flow pattern or the contaminant migration.

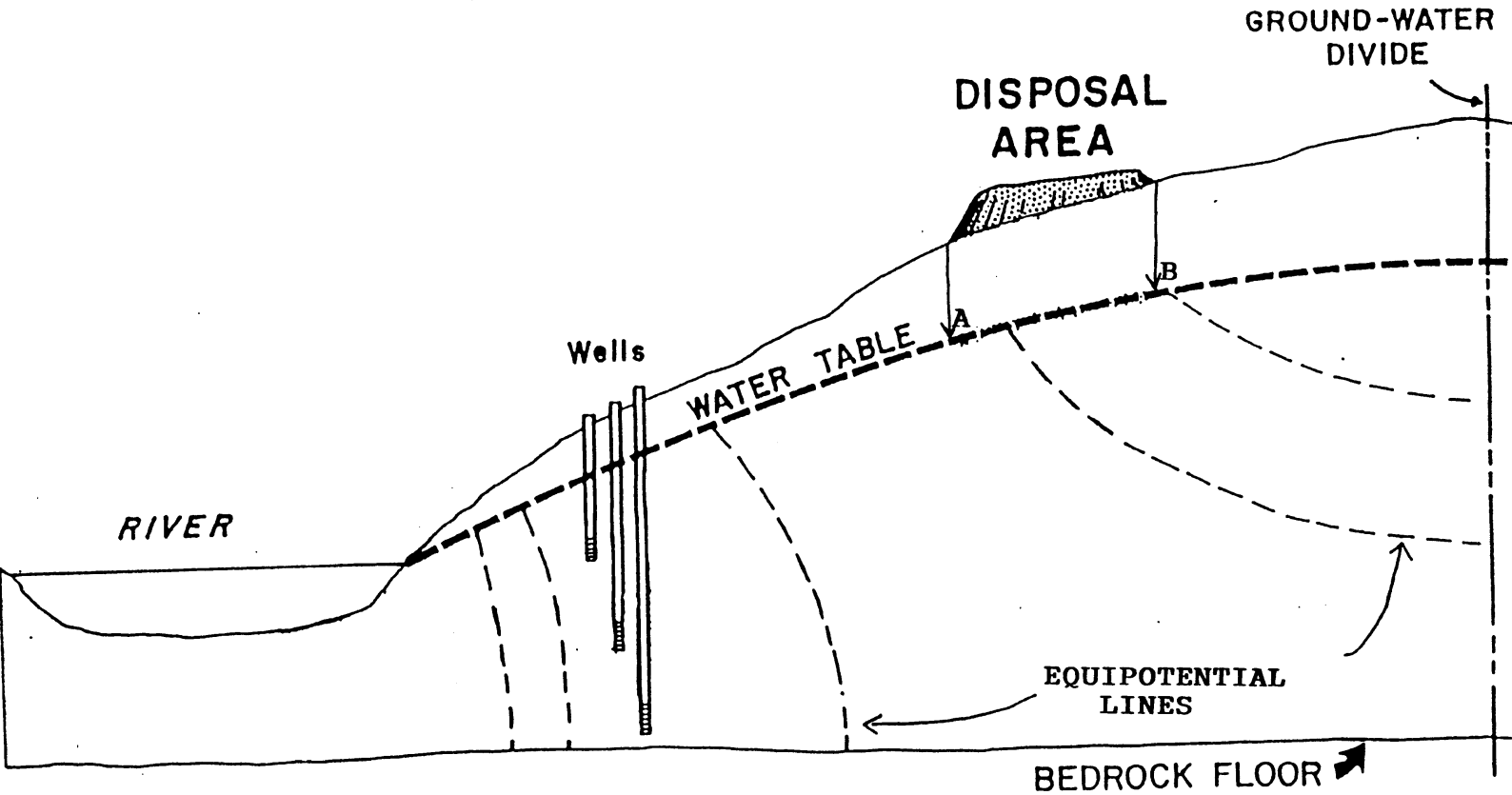


FIGURE 2.12

Flow of contaminants by advection in a water table aquifer. Source: Braids, Wilson and Miller, 1977.

Contaminant Flow

27) Which of the three wells will most likely become contaminated?

28) Where will the plume eventually end up?

So far this lab exercise has dealt with dissolved contaminants, but there is another very common type of contaminant. Non-aqueous phase liquids, or NAPLs, are pollutants, mainly hydrocarbon compounds, that do not readily mix with water; a few examples are gasoline, oil, and industrial solvents. Because these liquids do not readily mix with water they behave differently in the subsurface than do dissolved contaminants, and therefore they present special problems that require special attention. There are two types of NAPLs. **LNAPLs** (light non-aqueous phase liquids) have a specific gravity less than water (< 1.0), will float on top of the water table. **DNAPLs** (dense non-aqueous phase liquids) have a specific gravity greater than water (> 1.0); DNAPLs will sink through the saturated zone to the bottom of an aquifer. Figure 2.13 below lists the specific gravities for some NAPLs.

Organic Compound		Specific Gravity	
1	Acetone	.791	
2	Benzene	.879	
3	Bromodichloromethane	2.006	(15°C/4°)
4	Bromoform	2.903	(15°C)
5	Carbon tetrachloride	1.594	
6	Chlorobenzene	1.106	
7	Chloroform	1.49	(20°C liquid)
8	2-Chlorophenol	1.241	(18.2°C/15°C)
9	p-Dichlorobenzene (1,4)	1.458	(21°C)
10	1,1-Dichloroethane	1.176	
11	1,2-Dichloroethane	1.253	
12	1,1-Dichloroethylene	1.250	(15°C)
13	cis-1,2-Dichloroethylene	1.27	(25°C liquid)
14	trans-1,2-Dichloroethylene	1.27	(25°C liquid)
15	Ethylbenzene	.867	
16	Hexachlorobenzene	2.044	
17	Methylene chloride	1.366	
18	Methylethylketone	.805	
19	Methyl naphthalene	1.025	(14°C/4°C)
20	Methyl tert-butyl-ether	.731	
21	Naphthalene	1.145	
22	Pentachlorophenol	1.978	(22°C)
23	Phenol	1.071	(25°C/4°C)
24	Tetrachloroethylene	1.631	(15°C/4°C)
25	Toluene	.866	
26	1,1,1-Trichloroethane	1.346	(15°C/4°C)
27	1,1,2-Trichloroethane	1.441	(25.5°C/4°C)
28	Trichloroethylene	1.466	(20°C/20°C)
29	Vinyl chloride	.908	(25°C/25°C)
30	o-Xylene	.880	

FIGURE 2.13

Specific gravity for some organic compounds. Source: Nyer, Evan K., 1992, p. 50.

Contaminant Flow

Figure 2.14 on the following page shows an LNAPL spill and a DNAPL spill and the various aspects of each type that need to be considered when studying a NAPL spill.

Diagram **A** of Figure 2.14 above depicts a typical LNAPL spill. The sudden, large spill of diesel fuel moves through the unsaturated zone and rests atop the water table. The large volume of the diesel fuel will depress the water table because of it's weight, as shown in the picture. The space in the unsaturated zone where the LNAPL moved through it will have tiny droplets of pure diesel fuel in the pore spaces. These droplets are isolated from one another in the pores and therefore can not move; the droplets are stuck in place. This diesel fuel that has been left behind in the unsaturated zone as isolated droplets is known as **residual saturation.**

Diagram **A** also shows another common aspect of LNAPLs; LNAPLs commonly emit **volatiles** (vapors). Volatiles are particles of LNAPL that enter a gaseous phase and rise towards the surface through the unsaturated zone via pore spaces. In order for an LNAPL particle to become volatile it must be in contact with air, so vapors will only be emitted by any LNAPL above the saturated zone, and not from any dissolved form of the LNAPL.

Although LNAPLs are immiscible in water some particles may dissolve into the groundwater to form a contaminant plume as seen in Figure 2.14. Whether or not a NAPL will create a dissolved plume depends on it's **solubility**. If a NAPL has a high solubility it will easily dissolve some particles in water and create a plume. If a NAPL has a low solubility it may not dissolve to create a plume. Figures 2.15 and 2.16 show the volatility and solubility for various organic compounds.

Diagram **B** in Figure 2.14 shows a DNAPL spill of 1,1,1-Trichloroethane. Note that a DNAPL spill can have the same aspects as an LNAPL spill. The DNAPL may emit volatiles and have a dissolved plume associated with it and also leave residual saturation in the unsaturated zone. However, a DNAPL spill will also leave residually saturated droplets in the saturated zone as the spill moves downward towards the bottom of an aquifer.

Contaminant Flow

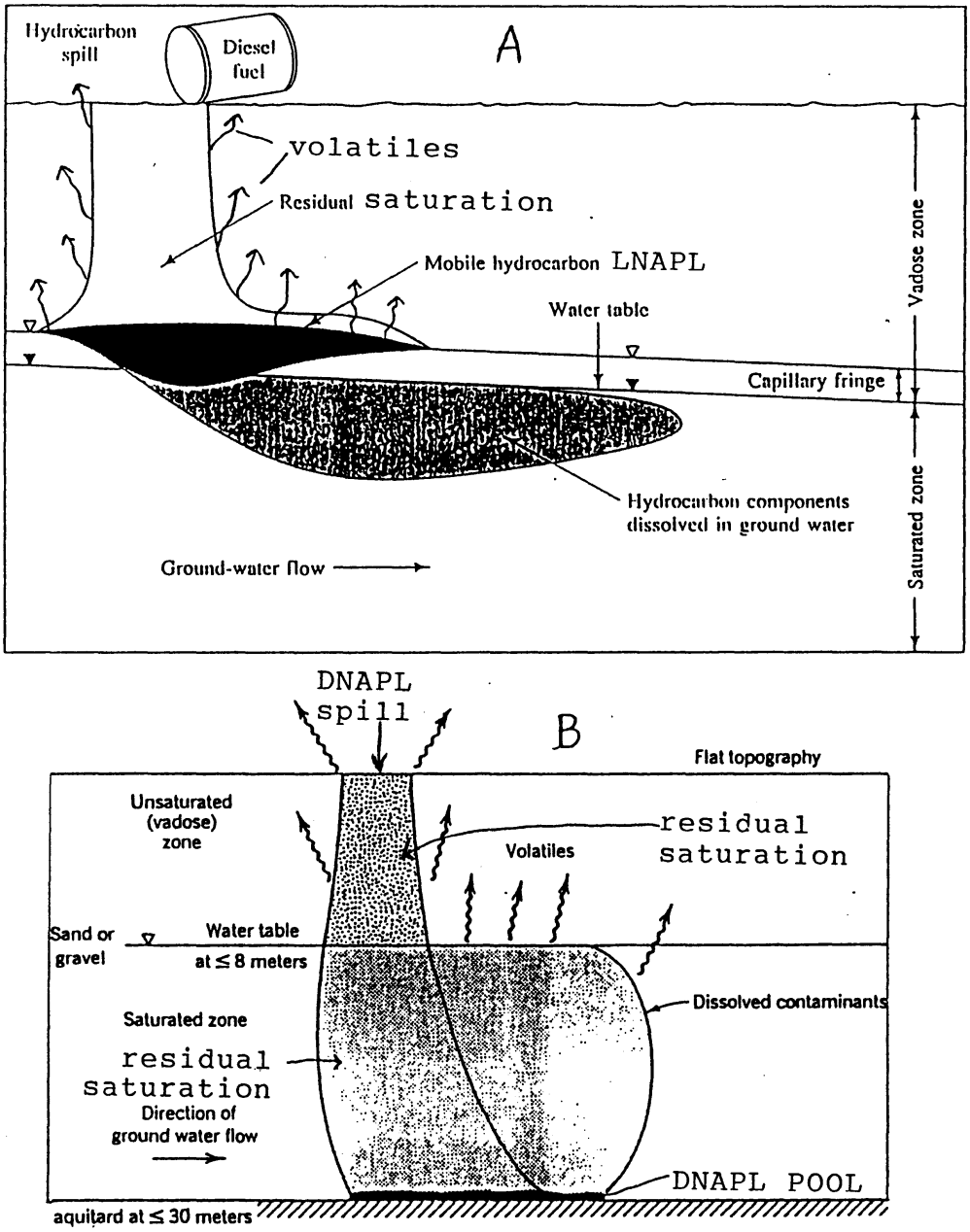


FIGURE 2.14

LNAPL and DNAPL spills. **A** depicts an LNAPL spill of diesel fuel; **B** shows a spill of 1,1,1-Trichloroethane. Sources: (LNAPL) Fetter, C. W., 1993, p. 221. (DNAPL) Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water-Prevention, Detection and Restoration. Copyright 1986. All rights reserved.

Contaminant Flow

A final aspect to consider about NAPLs is the direction of their flow. Because LNAPLs float on the water table, they will flow with the topography of the water table. DNAPLs, after reaching the base of the aquifer, will follow the topography of the bottom of the aquifer.

Compound	Formula	V.P.[1]
HALOGENATED HYDROCARBONS		
Dichloromethane	CH_2Cl_2	349
Trichloromethane	$CHCl_3$	160
Tetrachloromethane	CCl_4	90
Bromoform	$CHBr_3$	5.6 (25°C)
1,1-Dichloroethane	$CHCl_2CH_3$	180
1,2-Dichloroethane	CH_2ClCH_2Cl	61
1,1-Dichloroethene	$H_2C{=}CCl_2$	500
Trans-1,2-dichloroethene	$CHCl{=}CHCl$	200 (14°C)
1,1,1-Trichloroethane	CCl_3CH_3	100
Trichloroethene	$Cl_2C{=}CHCl$	60
1,1,2-Trichloroethane	$CH_2ClCHCl_2$	19
Tetrachloroethene	$Cl_2C{=}CCl_2$	14
AROMATIC HYDROCARBONS		
Benzene	C_6H_6	76
Phenol	C_6H_5OH	0.2
Chlorobenzene	C_6H_5Cl	8.8
Ethylenebenzene	$C_6H_5C_2H_5$	7
Toluene	$C_6H_5CH_3$	22
o-Xylene	$C_6H_4(CH_3)_2$	5
OTHER ORGANIC SOLVENTS		
Acetone	$CH_3{-}CO{-}CH_3$	89 (5°C)
Diethyl ether	$C_2H_5OC_2H_5$	442
Tetrahydrofuran	C_4H_8O	
1,4-Dioxane	$O(CH_2{-}CH_2)_2O$	30
BIOCIDES		
Pentachlorophenol	C_6Cl_5OH	1.1×10^{-4}
DDT	$(ClC_6H_4)_2CHCCl_3$	1×10^{-7}
Lindane	$C_6H_6Cl_6$	9.4×10^{-6}

FIGURE 2.15

Volatility of selected organic compounds. Source: Jackson, R. E., Patterson, R. J., Graham, B. W., Bahr, J., Belanger, D., Lockwood, J., and Priddle, M., 1985.

Note: The volatility of a pure compound equals the vapor pressure of the pure compound, per Raoult's Law.

[1] Compounds with vapor pressures less than 1 do not volatilize easily; compounds with vapor pressures greater than 1 will easily volatilize.

Contaminant Flow

	Organic Compound	Solubility (mg/l)
1	Acetone	1×10^{6}
2	Benzene	1.75×10^{3}
3	Bromodichloromethane	4.4×10^{3}
4	Bromoform	3.01×10^{3}
5	Carbon tetrachloride	7.57×10^{2}
6	Chlorobenzene	4.66×10^{2}
7	Chloroform	8.2×10^{3}
8	2-Chlorophenol	2.9×10^{4}
9	p-Dichlorobenzene (1,4)	7.9×10^{1}
10	1,1-Dichloroethane	5.5×10^{3}
11	1,2-Dichloroethane	8.52×10^{3}
12	1,1-Dichloroethylene	2.25×10^{3}
13	cis-1,2-Dichloroethylene	3.5×10^{3}
14	trans-1,2-Dichloroethylene	6.3×10^{3}
15	Ethylbenzene	1.52×10^{2}
16	Hexachlorobenzene	6×10^{-3}
17	Methylene chloride	2×10^{4}
18	Methylethylketone	2.68×10^{5}
19	Methyl naphthalene	2.54×10^{1}
20	Methyl tert-butyl-ether	4.8
21	Naphthalene	3.2×10^{1}
22	Pentachlorophenol	1.4×10^{1}
23	Phenol	9.3×10^{4}
24	Tetrachloroethylene	1.5×10^{2}
25	Toluene	5.35×10^{2}
26	1,1,1-Trichloroethane	1.5×10^{3}
27	1,1,2-Trichloroethane	4.5×10^{3}
28	Trichloroethylene	1.1×10^{3}
29	Vinyl chloride	2.67×10^{3}
30	o-Xylene	1.75×10^{2}

FIGURE 2.16

Solubility for various organic compounds. Source: Nyer, Evan K., 1992, p. 49.

Note: As a general rule, any compound with a solubility of 150 mg/L or more may be considered moderately to highly soluble.

Contaminant Flow

29) Figure 2.17 below shows a benzene source. Benzene is an LNAPL that is both volatile and soluble. Use this information to draw and label the benzene spill; be sure to include the volatiles, the dissolved plume, the pure benzene pool on the water table, and the area containing residual saturation.

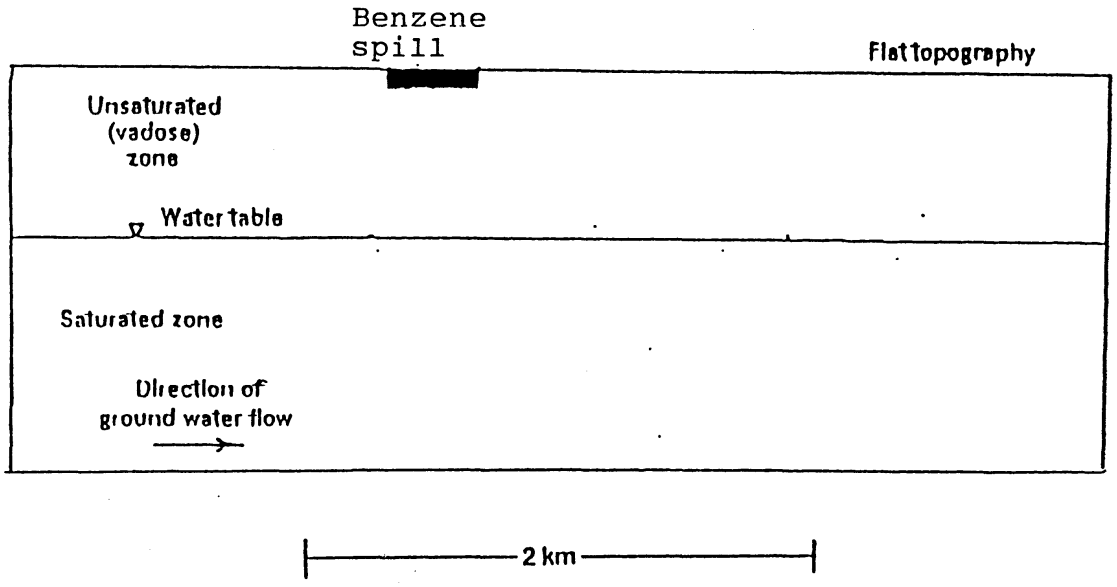


FIGURE 2.17

Benzene spill. Source: Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water-Prevention, Detection and Restoration. Copyright 1986. All rights reserved.

30) Figure 2.18 on the following page depicts an underground gasoline storage tank that is leaking. Knowing that gasoline is a soluble LNAPL; draw and label the LNAPL spill underground with all relevant aspects. Be sure to indicate the direction the LNAPL pool will flow.

31) Figure 2.19 on the next page depicts a DNAPL source. Knowing that this particular DNAPL is not readily volatile or soluble, such as pentachlorophenol, draw the spill; be sure to indicate the direction of flow of the pure DNAPL and the space affected by residual saturation.

Contaminant Flow

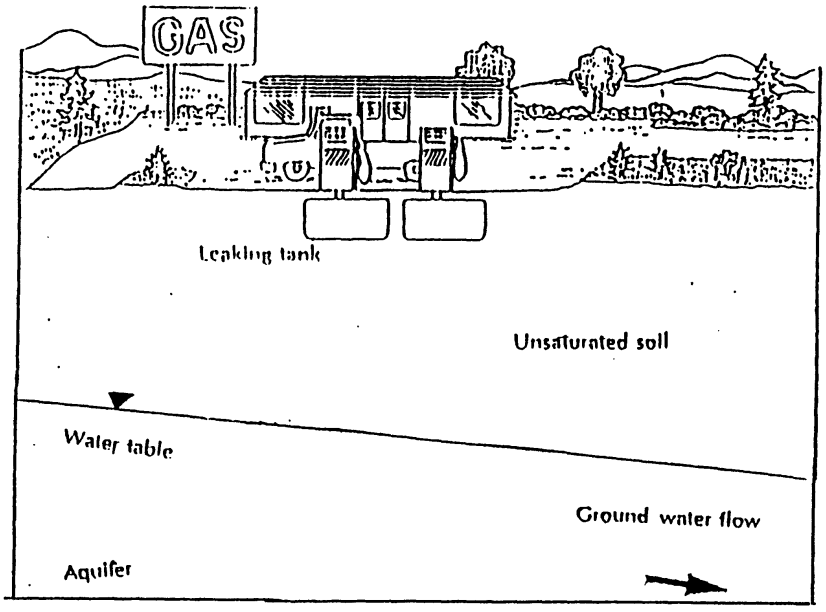


FIGURE 2.18
Gasoline tank leak. Source: Fetter, C. W., 1980, p. 416.

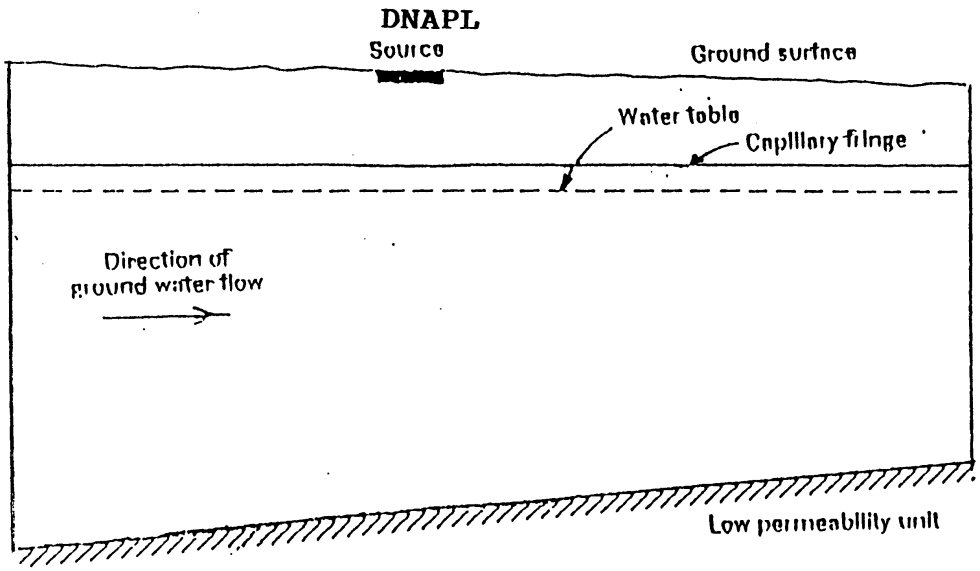


FIGURE 2.19
DNAPL spill. Domenico and Schwartz, 1990, p. 604.

Contaminant Flow

32) Figure 2.20 below shows both a DNAPL and LNAPL source. The LNAPL is methylethylketone, which has a vapor pressure less than 1; the DNAPL is phenol. Draw the spills with all relevant aspects; be sure to indicate the direction of movement for both pools of pure compound.

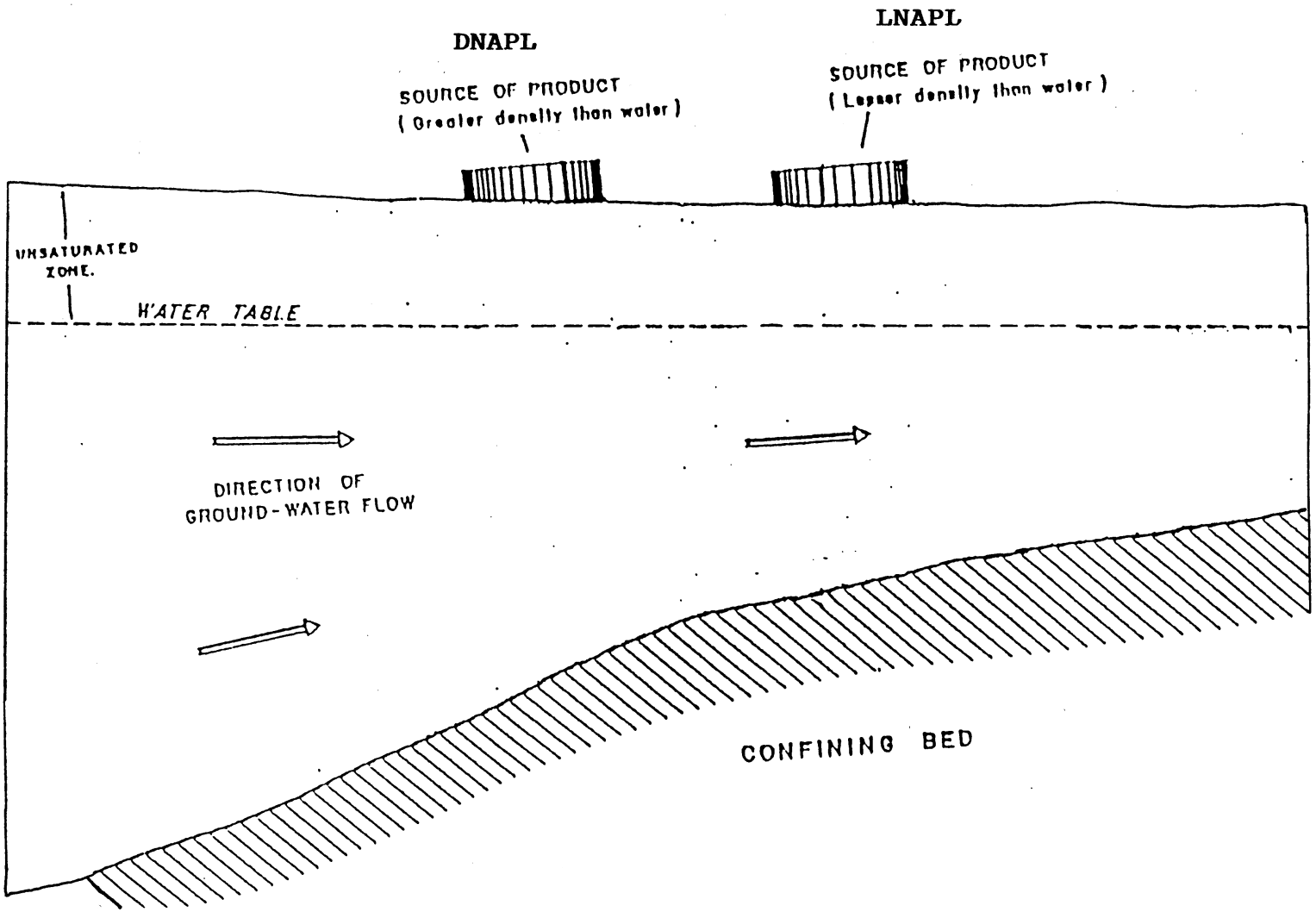


FIGURE 2.20
DNAPL and LNAPL spills. Source: Travis, C. C., and Etnier, E. L., 1984, p. 103.

Contaminant Flow

33) Diagram **A** of Figure 2.21 on the following page shows an oil spill floating on the water table and the residual oil left in the unsaturated zone. Assume during a dry period the water table is lowered as shown in diagram **B**. Draw the oil spill on the water table and the resulting area of residual saturation created when the water table was lowered.

34) During a period of heavy rainfall the water table was raised back to it's normal level as shown in part **C** of Figure 2.21. Draw the oil spill and the area with residual saturation again.

35) When the water table was recharged and it returned to it's normal level, what happened to the oil and the area with residual saturation?

36) What problems does the scenario in Figure 2.21 present to the environment?

Contaminant Flow

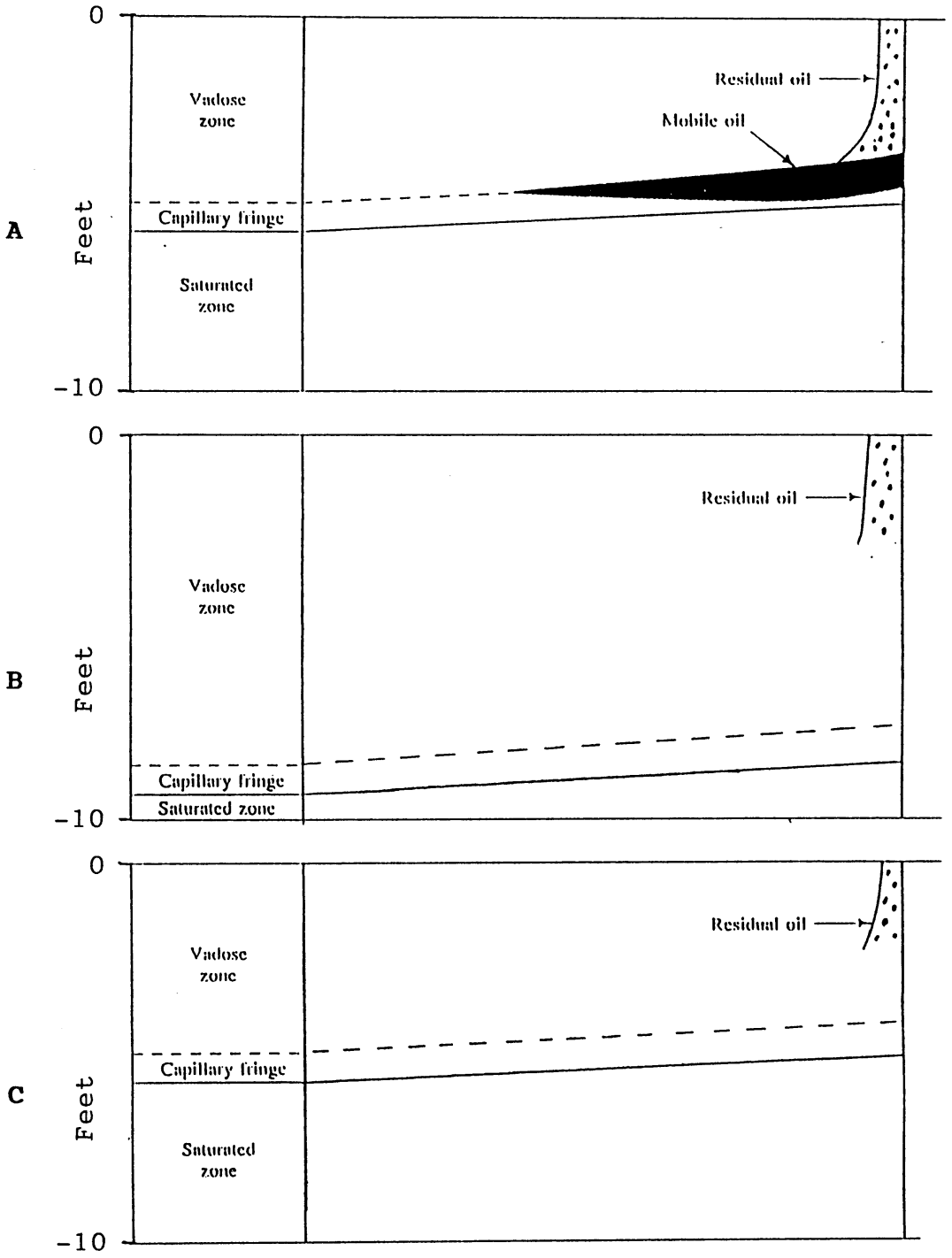


FIGURE 2.21

The effect of a lowering and rising water table on an LNAPL. Source: Fetter, C. W., 1993, p. 232.

Contaminant Flow

37) Figure 2.22 shows a gasoline spill which has reached the water table. In areas where the water table is at a shallow depth it is feasible to dig a trench to intercept the gasoline and then pump it out. On the figure draw a trench that would intercept and collect the gasoline.

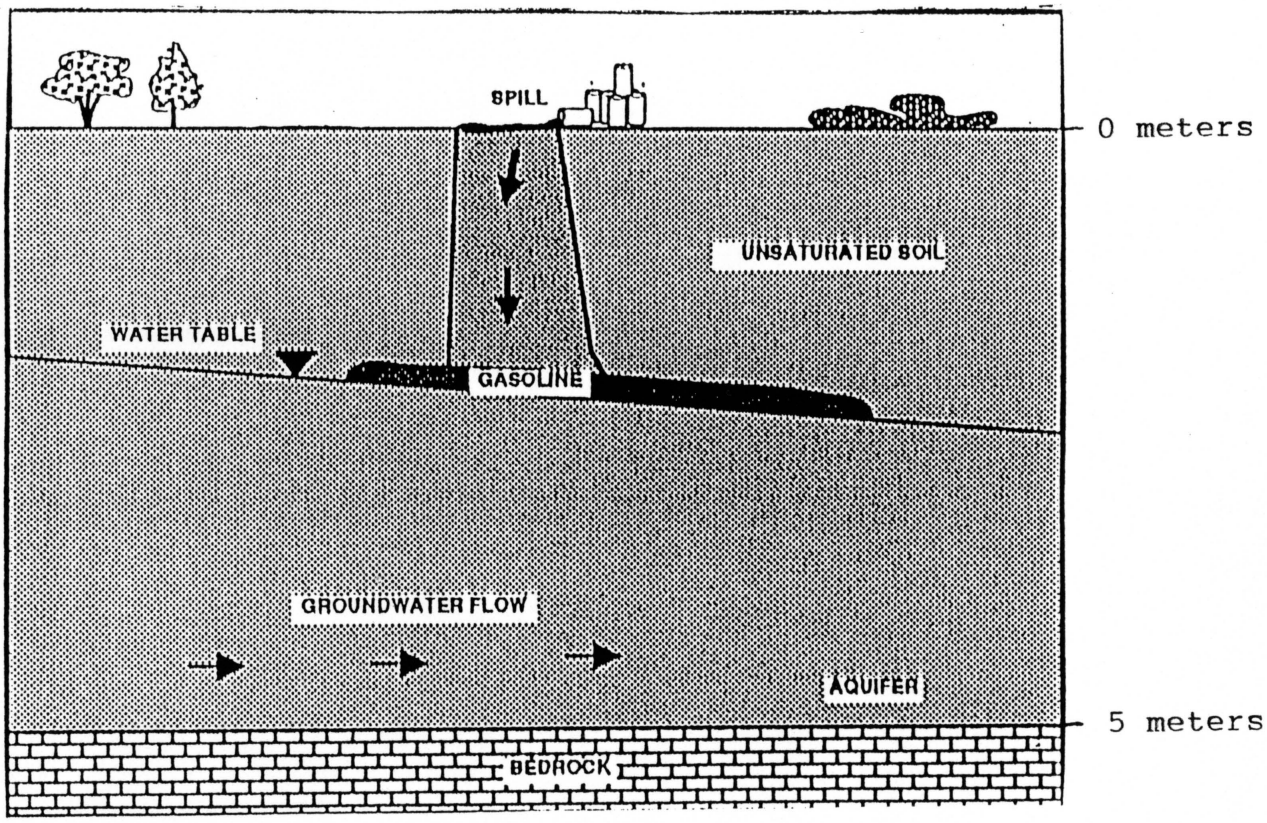


FIGURE 2.22

Gasoline spill on the water table. Source: Nyer, Evan K., 1992, pp. 52, 58.

38) Figure 2.23 on the next page pictures a gasoline spill which has reached the water table. In order to remove this spill, which is too deep to intercept with a trench, a well has been drilled at point **A** to pump out the gasoline. Draw the cone of depression that will result from pumping the well. The base of the cone has been started for you. Also include arrows which will show the groundwater flow directions inside and outside of the zone of influence of the pumping well.

Contaminant Flow

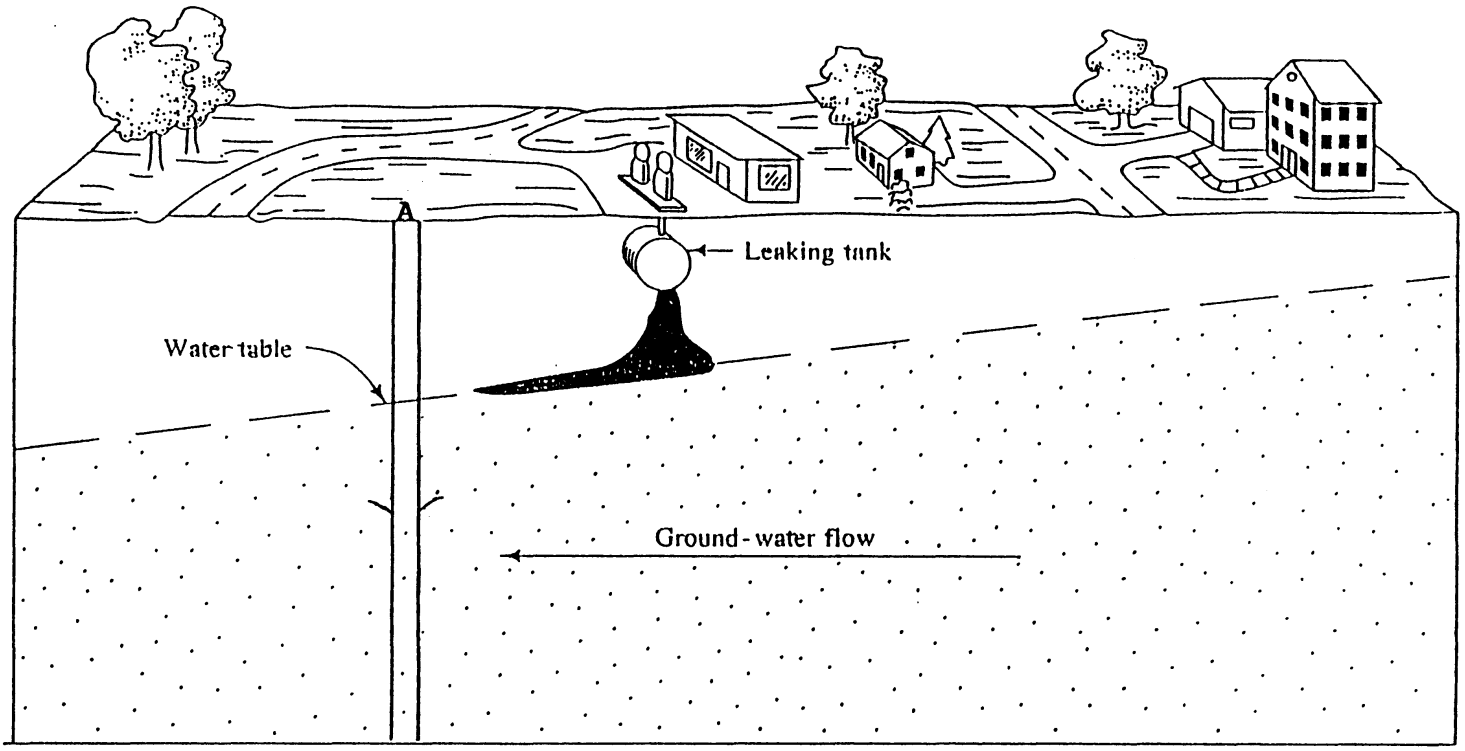


FIGURE 2.23
Gasoline spill approaching a well. Source: Fetter, C. W., 1993, p. 409.

39) What direction will the pool of gasoline move as a result of the pumping? Why? Draw this on Figure 2.23.

Figure 2.24 on the next page depicts a contaminant spill which has reached the water table and has created a dissolved plume. Two wells, a pumping well and a recharge well, have been installed to clean up the plume. The pumping well will withdrawal contaminated water and send it to a treatment unit to be cleaned. The clean water is then injected back into the aquifer down gradient from the plume. Examine Figure 2.24 and answer questions 40 and 41.

Contaminant Flow

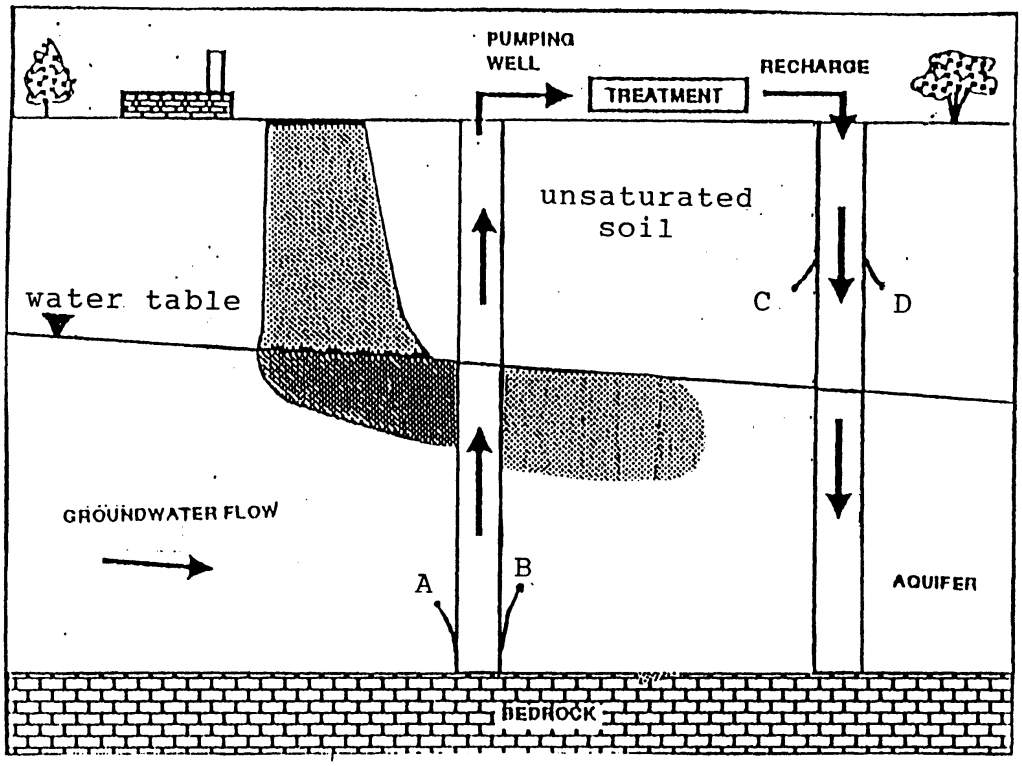


FIGURE 2.24
Pumping well and recharging well to remediate a dissolved plume. Source: Nyer, Evan K., 1992, p. 16.

40) Draw the cone of depression created by the pumping well and the cone of injection (an inverted cone of depression) created by the recharging well. Points **A**, **B**, **C** and **D** will help to start these cones. Indicate the direction of groundwater flow in the area to the left of the pumping well, in the area between the two wells and in the area to the right of the recharging well.

41) What is the result of placing a recharging well down gradient from the plume? What advantages are gained?

Contaminant Flow

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Contaminant Flow

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Answers To LAB 2

1) d = 58 meters, t = 647 days, v = 0.09 m/day

2) CTET: d = 17 meters, t = 380 days, v = 0.045 m/day
PCE: d = 8.75 meters, t = 380 days, v = 0.023 m/day

3) Darcy's equation for linear groundwater velocity is predictive. It is used when one is trying to determine groundwater velocity without the aid of a tracer. The relationship v = d/t is better to use when travel times and distances are known; it reflects the actual movement of a particle in an aquifer.

4) Adsorption causes CTET and PCE to move slower, because they are hydrophobic; these compounds would rather adsorb to mineral surfaces in the aquifer than be dissolved in water.

5) CTET: R_f = (0.09 m/d)/(0.045 m/d) = 2.0
PCE: R_f = (0.09 m/d)/(0.023 m/d) = 3.9

6) CTET: Mass = 0.37g/2.0 = 0.185g
PCE: Mass = 0.36g/3.9 = 0.092g

7) CTET: v = 25m/633days = 0.039 m/d
PCE: v = 12.3m/633days = 0.019 m/d

CTET: R_f = 0.09/0.039 = 2.3
PCE: R_f = 0.09/0.019 = 4.7

The R_f values are larger for 633 days; R_f is increasing over time and distance.

8) CTET: Mass = 0.37g/2.3 = 0.16g
PCE: Mass = 0.36g/4.7 = 0.076g

There is less CTET and PCE dissolved in the water and more adsorbed onto the aquifer after 633 days.

9) Adsorption.

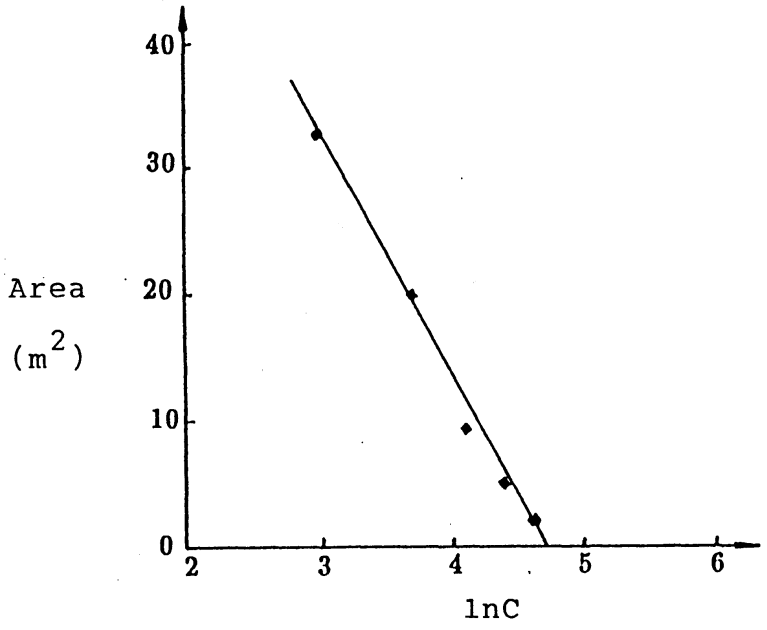
10) Biotransformation.

Answers To LAB 2

11)

a/b	$C(mg/l)$	$a(m)$	$b(m)$	lnC	$A(m^2)$
2.239	100	1.119	0.500	4.605	1.758
1.732	80	1.642	0.948	4.382	4.890
1.667	60	2.239	1.343	4.094	9.447
1.604	40	3.172	1.978	3.689	19.711
1.565	20	4.040	2.575	2.996	32.601

12)



13) Slope = -18.45

14) t = 121 days. $D_L D_T$ = 0.0001474

15) Average a/b = 1.76 D_L/D_T = 3.1

16) D_L = 0.2138 D_T = 0.0069

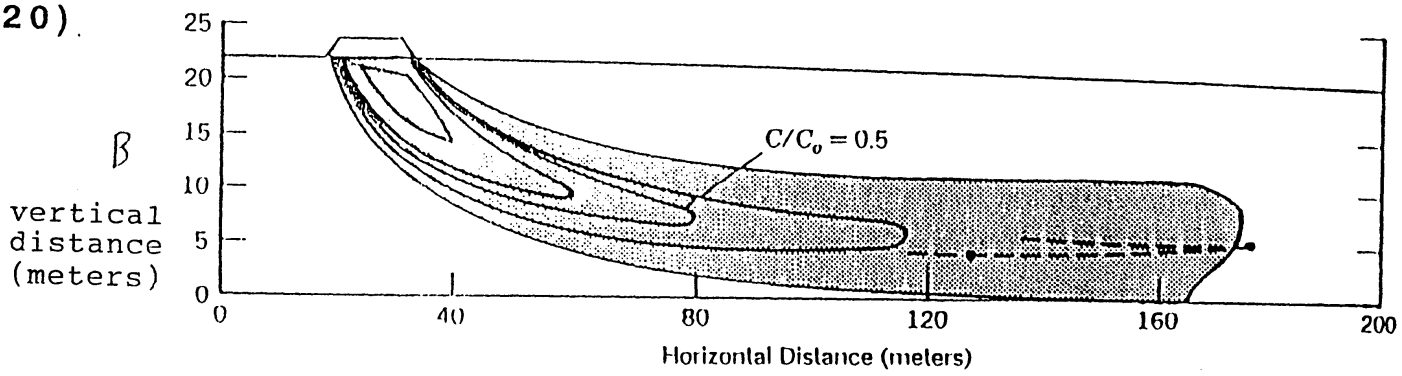
17) a_L = 0.09 m a_T = 0.03 m

Answers To LAB 2

18) Longitudinal dispersion is greater.

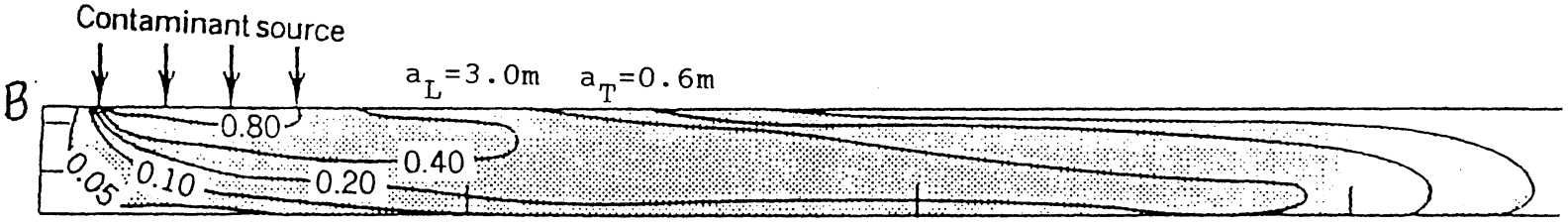
19) The results should be consistent.
$D_L > D_T$ $a_L > a_T$

20)



21) The new plume is thicker; the increase in vertical transverse dispersivity causes more vertical spreading of the contaminant. The vertical spreading results in the plume being shorter in the longitidinal direction.

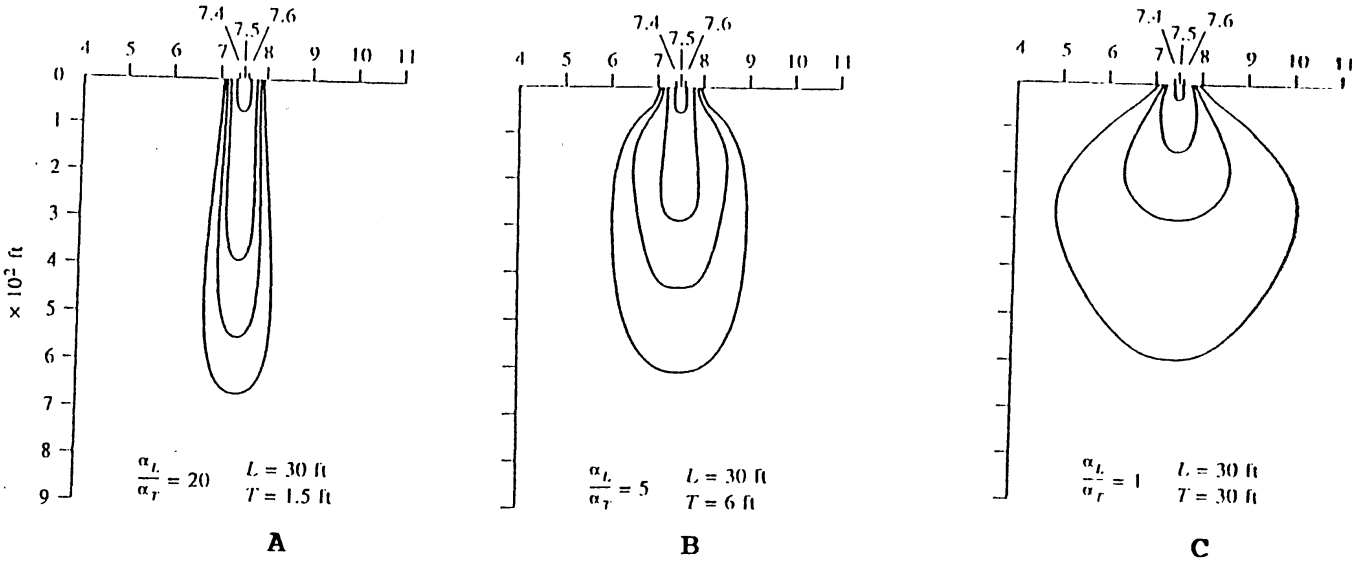
22)



23) The increase in a_T causes the plume to increase it's size vertically. The increase in a_L does not cause the plume to be longer or shorter, but it causes a decrease in concentrations down gradient from the source because the contaminant is mixing with a greater proportion of clean water.

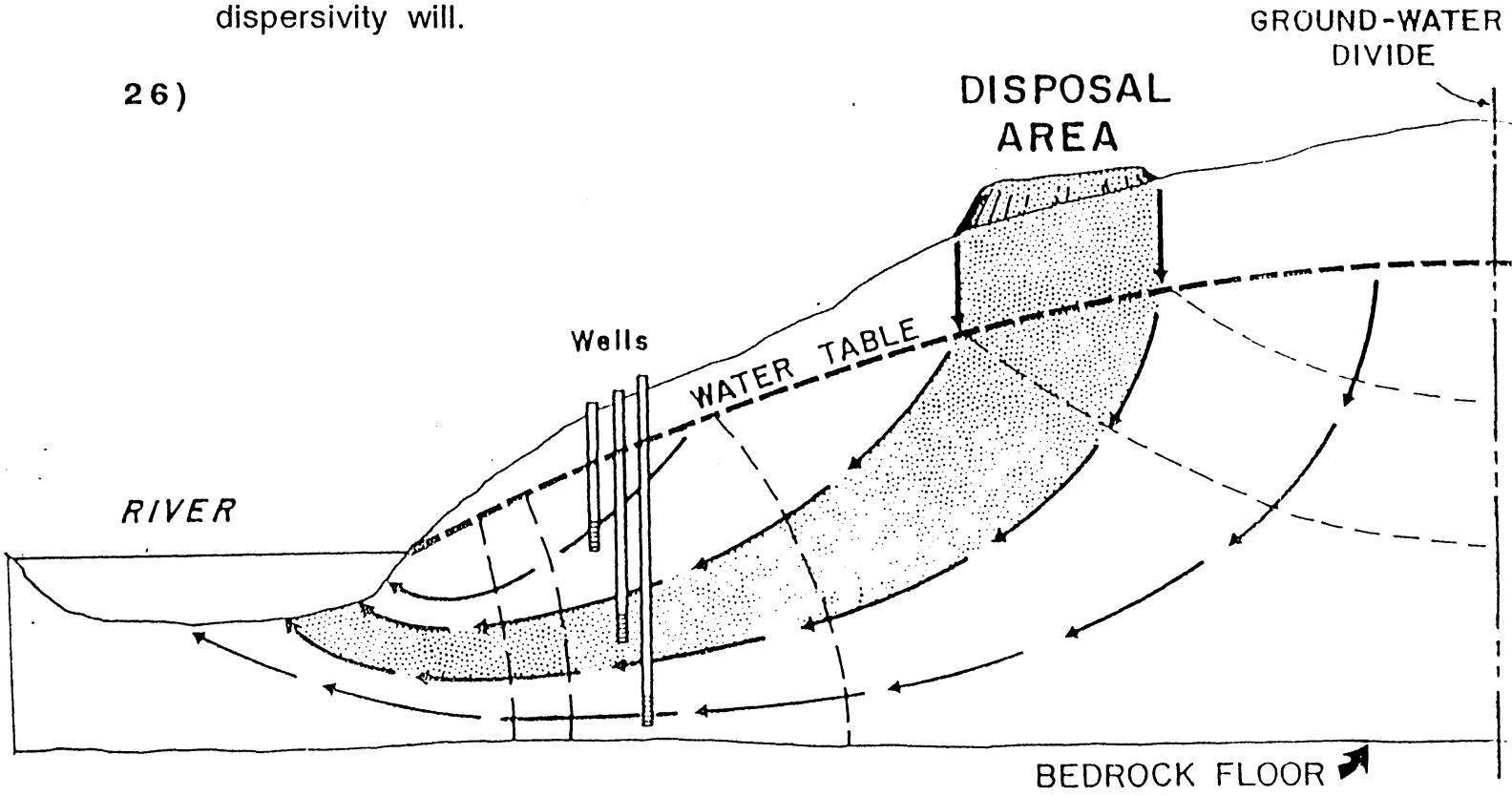
Answers To LAB 2

24)



25) Yes, increasing the horizontal transverse dispersivity makes the plume thicker and shorter, just as an increase in vertical transverse dispersivity will.

26)

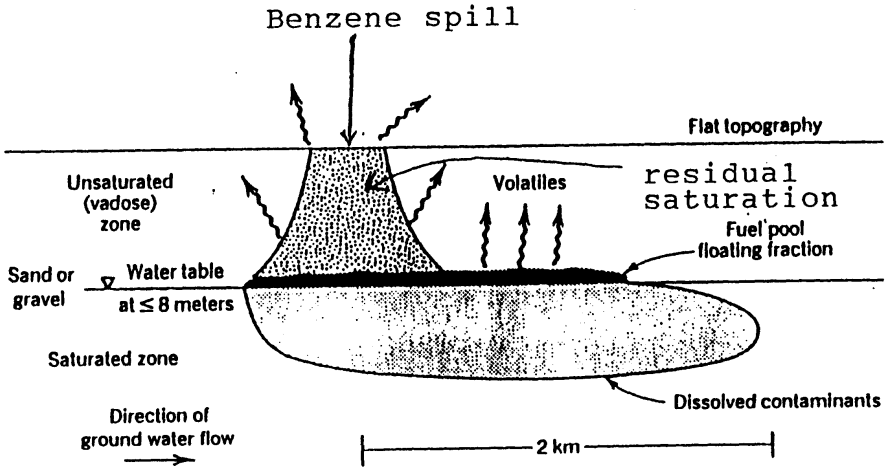


27) The middle well will most likely become contaminated.

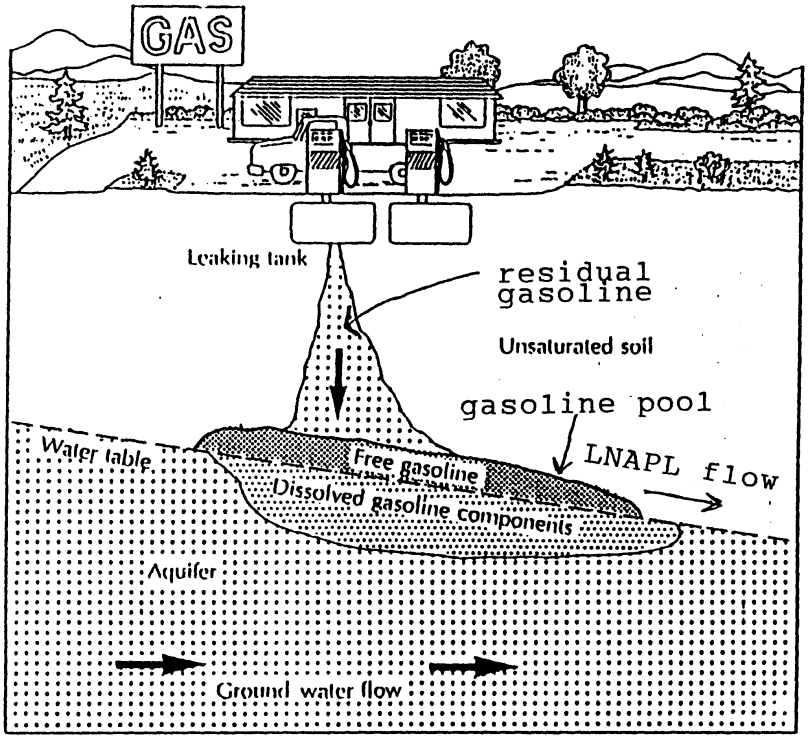
Answers To LAB 2

28) The plume will eventually end up in the river.

29)

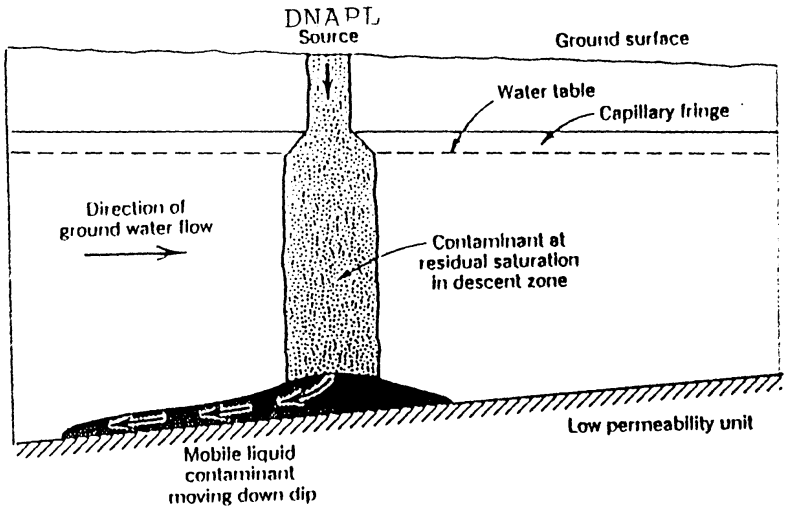


30)

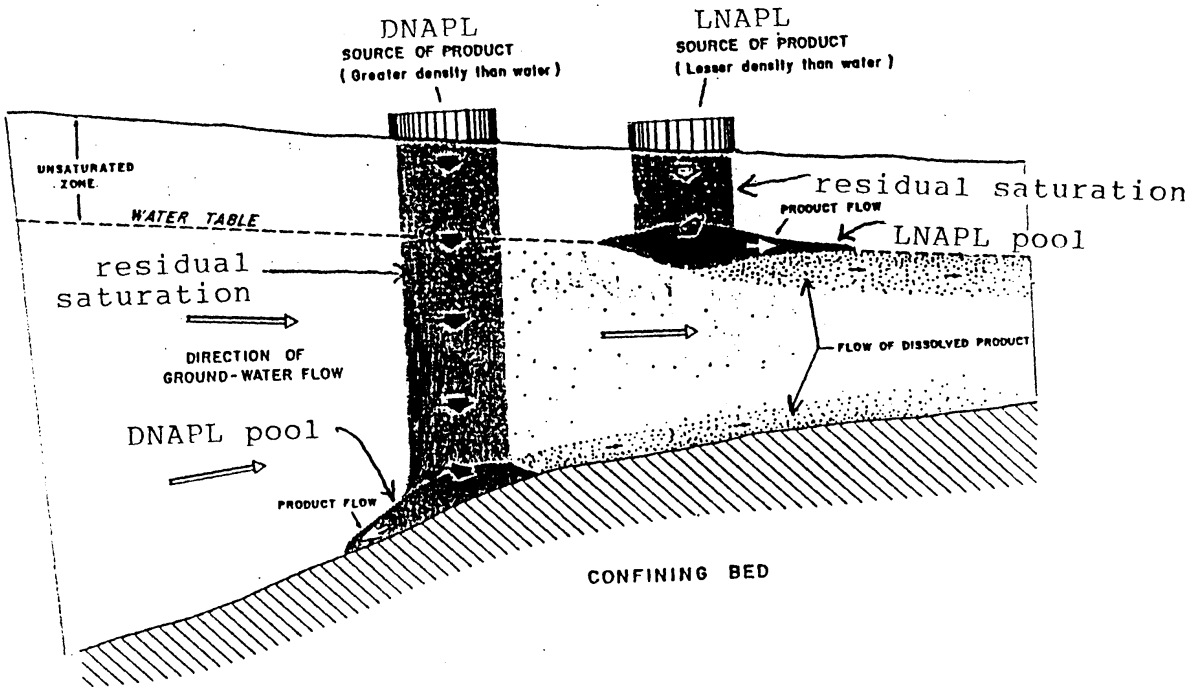


Answers To LAB 2

31)

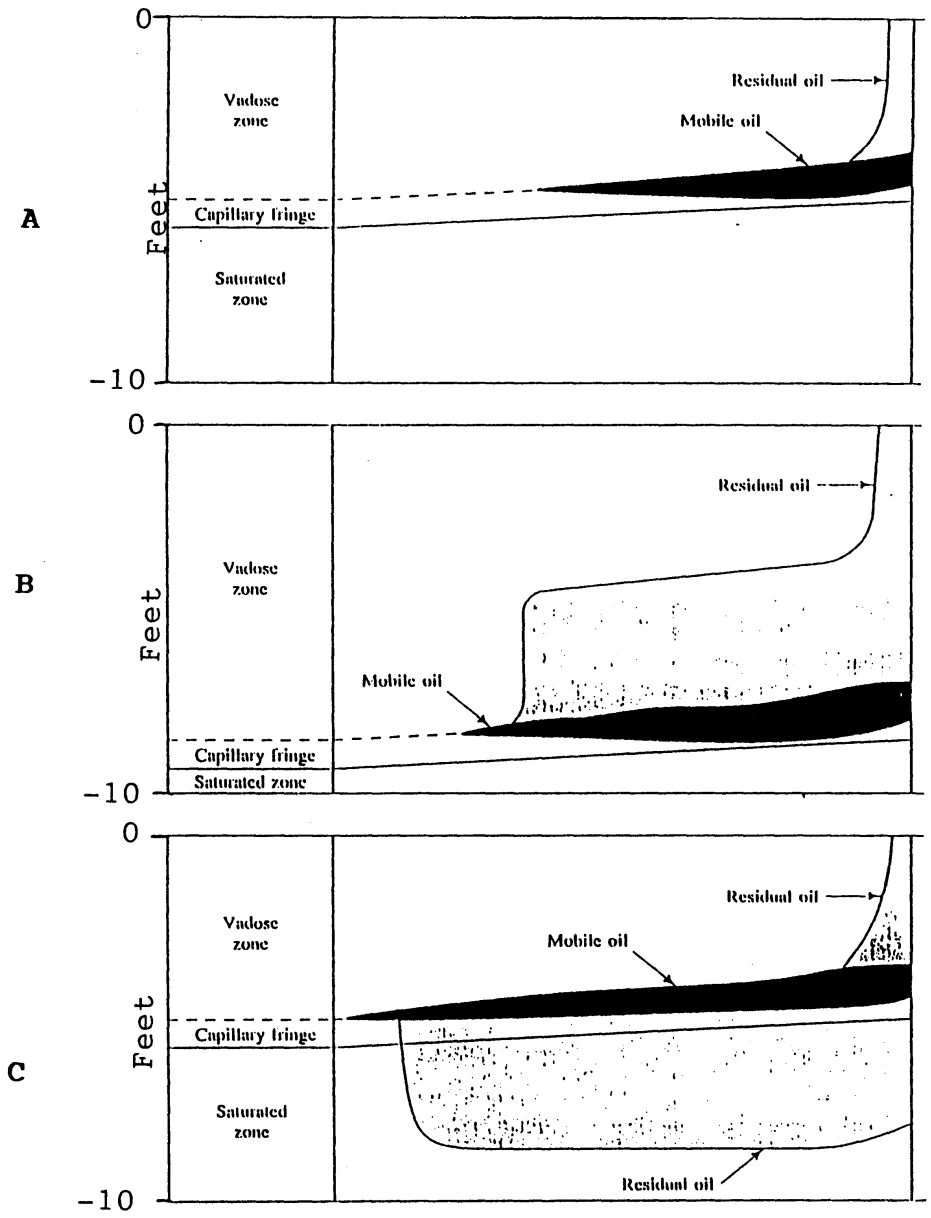


32)



Answers To LAB 2

33), 34)

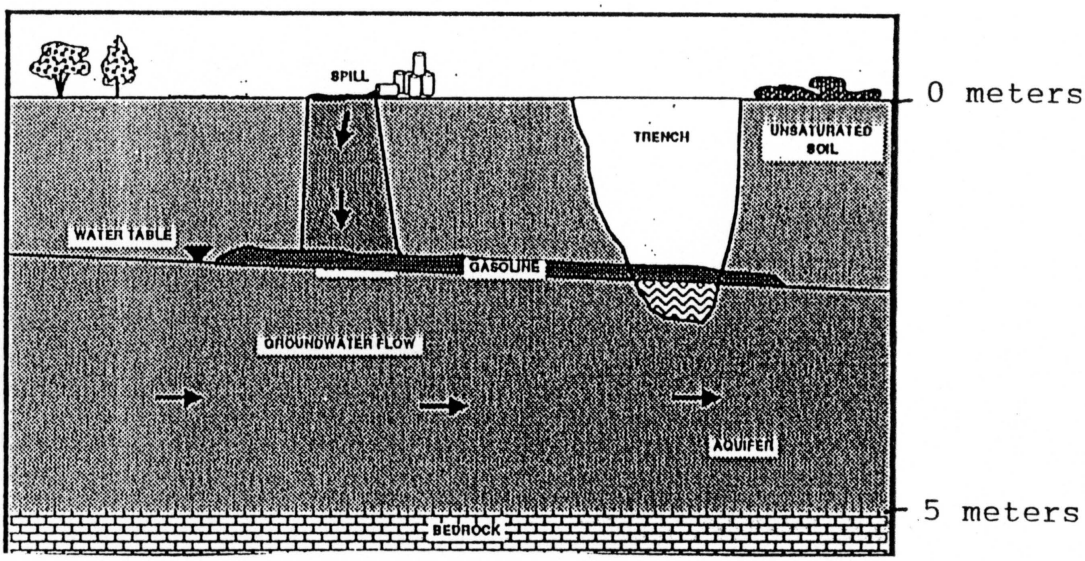


35) The oil rose with the water table, but the area contaminated by residual saturation is now in the saturated zone.

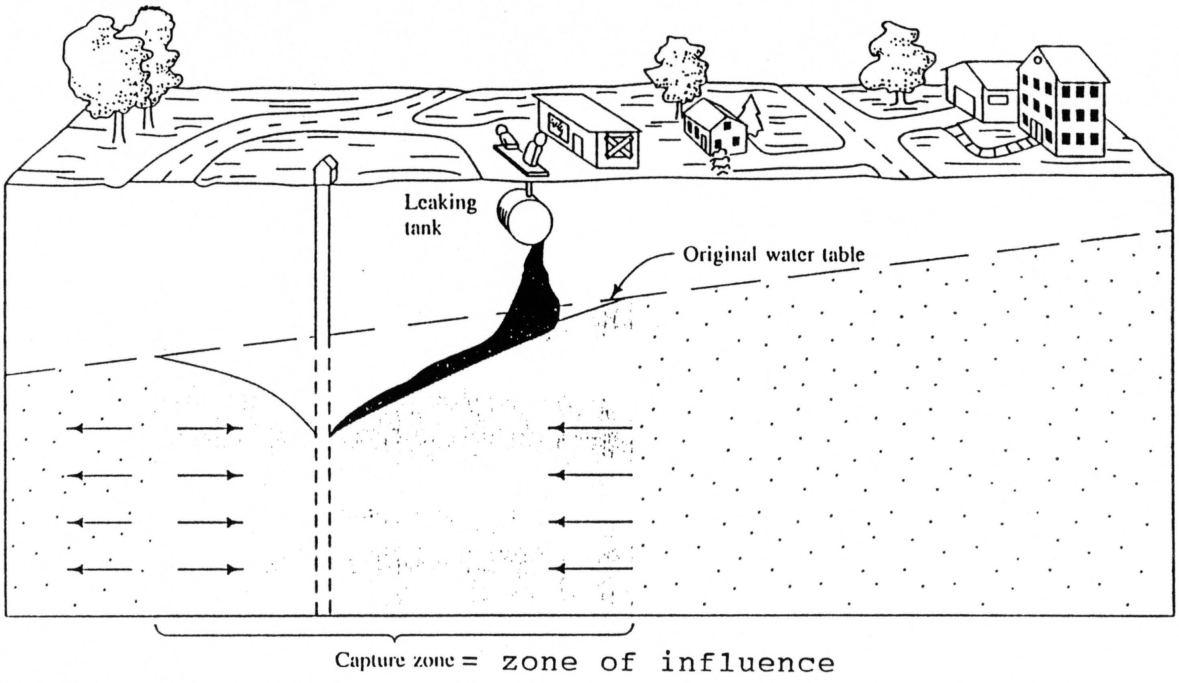
36) The aquifer now has pure oil residually saturated in it's pores. This could cause a dissolved plume to spread down gradient. Even if the plume is removed by a pumping well, there is still contaminant at residual

36) (Continued) saturation in the saturated zone which will create another plume.

37)



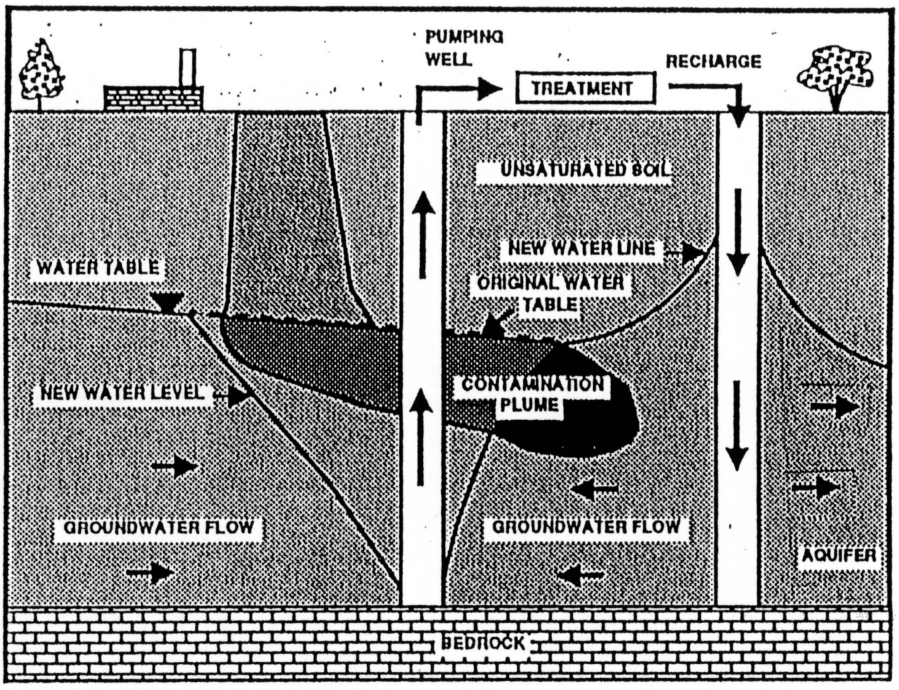
38), 39)



The gasoline will flow into the cone of depression because LNAPLs follow the topography of the water table. Thus, the gasoline is removed from the water table.

Answers To LAB 2

40)



41) The recharging well will reverse the flow direction at the tip of the plume and send the contaminant towards the pumping well to be extracted. This allows the contaminant to be removed more quickly and prevents the contaminant particles at the leading edge of the plume from escaping the pumping well.

CONCLUSION AND FUTURE WORK

Upon researching and writing this thesis I discovered that my knowledge of the subject material must be thorough. Many concepts and terms which I thought I understood well were suddenly not so clear. As a result, I spent many hours reading my text books to be certain I could accurately explain and define hydrogeologic ideas and terms. I felt it was crucial that I completely understood an idea before I could attempt to teach another student that same idea. So, in writing these labs I have given myself a better understanding of many fundamental concepts in hydrogeology; I hope that other students will gain a greater knowledge of this topic from reading or working these exercises. These exercises provide the basis for understanding two important areas of hydrogeology - groundwater flow and contaminant movement.

Future work in this area might include exercises dealing with water chemistry, groundwater resources development and management, and contaminant remediation. The contaminant flow exercise has several problems at the end dealing with remediation. Although this area of hydrogeology is worthy of study I decided not to include much on this topic because it could easily encompass a lab by itself, and the contaminant flow lab is already quite long.

The final steps in preparing these exercises are beyond the scope of this thesis. The exercises should be tested by

undergraduate students in the sciences and by graduate students in both the Geological Sciences and Science Education. After evaluating the performance and comments of these students, the exercises should be revised to meet the educational needs of students who will use them.